House characteristics and indoor dampness and mould in three New Zealand House Condition Surveys conducted in 2005, 2010 and 2015.

A thesis by publications presented in partial fulfilment of the
requirements for the degree of

Doctor of Philosophy

in

Engineering

At Massey University, Wellington, New Zealand

Phoebe Taptiklis

2023

Abstract

Indoor dampness is a common exposure associated with adverse health effects such as asthma and respiratory infections. This thesis aimed to improve understanding of the determinants of indoor dampness by analysing three New Zealand House Condition Surveys. The methodology included assessing associations between house characteristics and five assessments of indoor dampness (inspector-assessed subjective dampness, visible mould, musty odour and moisture measured in ceiling and floor joists). Using multivariate regression, the analyses showed that better insulation and ventilation were associated with less indoor subjective dampness, visible mould and musty odour, but were not associated with moisture measurements. Rental tenure and higher occupancy were associated with more subjective indoor dampness, visible mould and musty odour, and no associations were observed with moisture measurements. Poorer conditions of the subfloor (insufficient ventilation, absence of a ground vapour barrier and evidence of ponding or leaks) were associated with more subjective indoor dampness and higher moisture measured in the floor joists. Poorer condition, cumulatively, of five elements of the building envelope (condition of: roof, cladding, windows, exterior paint and spouting and guttering) was associated, in a dose-dependent manner, with more subjective indoor dampness, visible mould (including when restricted to bedrooms and living rooms only), musty odour and higher measured moisture in floor joists. Moisture in ceilings and floor joists were weakly correlated with each other, and with subjective dampness and musty odour, but moisture in joists was not associated with visible mould. The main conclusion is that the building envelope condition is an important determinant of indoor dampness. Also, the results described in this thesis strongly suggest that a single measure of indoor dampness may not fully capture the most relevant exposure; as a consequence, for future epidemiological studies on the health effects of indoor dampness, it may be best to collect (and analyse) several measures of indoor dampness.

Acknowledgements

This thesis was supported by many groups and people. Thanks firstly to BRANZ for both the scholarship and making the data available. Thanks to my supervisors for seeing me though this experience. Thanks to all my PhD buddies for helping me know it wasn’t just me. Thank you to my son, my family, and my friends for being generally awesome.

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1. General introduction

This thesis focusses on exposure assessment of indoor dampness with the aim of improving understanding of its determinants. In particular, the work described in this thesis aimed to improve understanding of the associations between house characteristics and indoor dampness, mould and moisture measurements. It is estimated that people in Western nations spend 90% of their time indoors, with the bulk of that, close to 70%, is in our own homes [1]. This suggests that harmful exposures from our homes may have a significant impact on public health. Vulnerable members of society often spend even more time at home and are thus potentially even more impacted by its environment, particularly as they are also often more susceptible to the harmful exposures in the indoor environment.

There is strong evidence of links, suggestive of causality, between living in a home with visible mould or signs of water damage and asthma, allergies and respiratory illness [2-8], as well as other health outcomes. For example, a large analysis and review of European housing and health status (LARES), published in 2009, found that damp housing was associated with a 70% increased risk of reporting ill health from a wide range of illnesses, including asthma, bronchitis, arthritis, anxiety, depression, migraine and gastrointestinal illness [9]. More recently, other studies have reported associations between damp housing and a higher likelihood of gastrointestinal illness [10, 11], rheumatic fever [12] and chronic obstructive pulmonary disease (COPD) [13]. Some of these health effects are serious and may last much of the lifespan, such as asthma, COPD and rheumatic fever (which can develop into rheumatic heart disease), thus contributing to a significant health burden to both the individual and society.

It is widely assumed that much of damp-housing related illness is caused by mould - either spores, fragments or metabolites - however the causal mechanism remains unclear, and evidence directly linking quantitative mould measurements and health effects remains tenuous [14, 15]. Also, mould is not the only harmful exposure associated with dampness. Other exposures include bacteria and yeasts as well as synthetic exposures such as phthalates and formaldehyde, all of which are more prevalent in houses with dampness [16-20]. The likely reason why exposures to these chemicals are elevated in damp indoor environments is that dampness in materials containing these chemicals can increase the rate at which they are released into indoor air, thereby increasing airborne levels in these indoor environments.

The questions surrounding causation have led many researchers to focus on linking adverse health effects directly to (dampness-related) house characteristics. House characteristics linked with adverse health impacts include damp subfloors or basements [21-23], type of ventilation [17, 24-26], low ventilation rate [27], house age [26, 28], house size [29]. While studies such as these help to tie the adverse health impacts to the house, and point toward potential interventions, they generally look only at a limited selection of house characteristics, meaning residual confounding (by other interrelated characteristics) cannot be discounted. An example being house age, which may be related to dampness (and poorer health) because older houses are generally in a poorer state of repair than newer houses, leading to increased likelihood of water intrusion from the exterior. Studies which have assessed poor repair are consistent in reporting increased likelihood of dampness and mould indoors [30-33].

As well as linking house characteristics to poorer health, epidemiological studies have also reported associations between specific house characteristics and various assessments of indoor dampness, mould or moisture measurements. This large repository of information, from many studies over the past half century, will be reviewed in Chapter 2 of this thesis.

Prevalence of indoor dampness and mould in homes has been estimated at 21% in European homes [34, 35], 47% in US homes [36] and 55% in Chinese homes [37, 38]; however, without a consistent definition for dampness (see below), such comparisons are not always valid. In 2018, the prevalence of (self-reported) dampness was assessed for the first time in the New Zealand census, with findings showing that 21.5% of homes were considered damp some, or all of the time [39]. Other studies from New Zealand have reported much higher levels of up to 59% when inspections by researchers or construction professionals are included [40, 41]. Even using the lower prevalence figures, it suggests that a large number of people in New Zealand are impacted by exposure to these harmful conditions.

As alluded to above, there is currently no widely-accepted definition of indoor dampness, and, as a consequence, there are no standardised measurement protocols [42]. In addition to hindering research into the health effects of indoor dampness, it also complicates research aimed to identify house characteristics associated with indoor dampness and mould, which is critically important for the development of effective interventions. While it is not expected that this thesis will be able to provide a definition of house dampness or recommend standard protocols, the research aims to provide a useful step towards those outcomes (see specific aims below). This will be achieved by assessing associations between specific housing characteristics and indoor dampness, mould, musty odour or moisture measurements using three iterations of the New Zealand House Condition Surveys conducted in 2005, 2010 and 2015.

The New Zealand Building Research Association (BRANZ) has conducted national population-based surveys of housing approximately every five years since 1994, and data from the three most recent surveys (2005, 2010 and 2015) have been used for this PhD research. These surveys are extremely detailed, comprising over 1500 individual items of assessment about the physical characteristics of the house and location, as well as some details on the household, most importantly the number of occupants and whether they are owner occupiers or tenants. In addition, moisture measurements in ceiling and floor joists were collected and assessments of indoor dampness (subjective sensation), visible mould (on internal surfaces in each room) and the presence of a musty odour (a single overall assessment) was also recorded.

Previous analyses of these surveys have consistently shown a difference in indoor dampness and mould by tenure, with rental houses having consistently higher prevalence of indoor dampness, mould and musty odour [43-45]. This association will be examined for possible confounding by other available variables, for example, occupancy, ventilation and insulation, as well as condition. Likewise, the commonly reported association between indoor dampness and house age [22,26,34], can be examined for potential confounding effects, in particular, by physical condition parameters. Because this research is focussed towards identification of exposure determinants, rather than exposure indicators, emphasis is placed on explanatory variables that are plausibly related to the causation of indoor dampness problems (for example condition of waterproofing elements, and aspects of house typology).

For a full list of house characteristics and dampness indicators used in this research, and the manner in which they were treated in the analyses, the reader is referred to Appendices 1 and 2.

The aims of this thesis are therefore to assess:

1. Associations between house characteristics and inspector-rated subjective indoor dampness, visible mould and musty odour, and measured moisture in ceiling and floor joists (Chapters 3 and 4);
2. Whether poorer condition of specific building components, particularly those comprising part of the building envelope (waterproofing elements) is associated with indoor dampness indicators or moisture measurements (Chapters 3 and 4);
3. Whether an overall poorer house maintenance rating is associated with indoor dampness indicators and moisture measurements (Chapters 3 and 4);
4. Dose-response associations with aggregated domains of housing condition, ventilation, insulation, and subfloor defects with dampness outcomes (Chapters 3 and 4);
5. Whether associations with mould, when restricted to only living and bedrooms (excluding kitchens and bathrooms where mould may be considered more common), are similar or different to associations when considering mould anywhere in the house.

6. Associations (including dose-response associations) between dampness indicators and measured moisture levels (Chapter 5)
7. Whether indoor dampness is influenced by different climate zones across New Zealand, and by recent weather patterns (Chapters 3, 4 & 5)

1.1 Outline of the thesis

Chapter 1 – General Introduction

This chapter provides a brief introduction to the thesis, including a brief background on the relationship between damp housing and health, then more specifically focusing on the knowledge gaps pertaining to this research topic – the relationship between house characteristics and indoor dampness. The aims of this thesis are then presented, followed by an outline of the chapters.

Chapter 2 – Literature review

This chapter comprises a systematic review of the literature on house characteristics and indoor dampness, mould, odour and indoor moisture measurements. The database search was initially conducted in August 2017 and updated in April 2022. In total, 63 published studies were included that reported on associations between house characteristics and indoor dampness, mould, musty odour or moisture measurements in surveys of occupied houses.

Chapter 3 – House characteristics and condition as determinants of visible mould and musty odour: Results from three New Zealand House Condition Surveys, in 2005, 2010 and 2015 (Taptiklis et al., (2021). Indoor Air 31(3). 818-831)

This chapter describes in detail the methods and results of the study that assessed associations between house characteristics and indoor visible mould – both in the whole house, and in the living and bedrooms only – and musty odour. The implications of the results are discussed, and conclusions drawn.

Chapter 4 – Associations of house characteristics with indoor dampness and measured moisture: Results from three New Zealand House Condition Surveys in 2005, 2010 and 2015. (Taptiklis et al., (2022). Building and Environment 208, 10.1016/jbuildenv.2021.108508)

This chapter describes in detail the methods and results of a study that assessed associations between house characteristics and inspector-assessed subjective indoor dampness and moisture measurements taken from ceiling and floor joists. The implications of these results are discussed, and conclusions drawn.

Chapter 5 – Interrelationships between five indoor dampness measures across three New Zealand House Condition Surveys, in 2005, 2010 and 2015.

This chapter describes in detail the methods and results of a study that assessed interrelationships between the dampness indicators and moisture measurements taken from ceiling and floor joists. The interrelationship is discussed and conclusions provided alongside an examination of the methodological strengths and limitations.

Chapter 6 – General Discussion

This chapter summarises the main findings of the studies described in this thesis. It provides further discussion based on a synthesis of the results throughout the thesis. The overall strengths and limitations of this body of research is discussed, and finally recommendations for future research are provided including recommendations for improved data collection protocols.

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2 Literature review

2.1 Introduction

Damp housing is an important public health risk [1]. However, there is no widely accepted definition by which a house can be categorised as damp [2], and there is no threshold of moisture measurement above which dampness can be established [3]. Despite this, living in a house with higher rates of several qualitative measures including visible mould, damp spots, water stains, condensation, and musty or mouldy has been associated with asthma exacerbations [4], and new onset asthma in children [5, 6] and adults [7]. The evidence for these associations being causal is now considered strong [8]. Other adverse health effects associated with, and possibly caused by, living in a damp house, include rhinitis [6, 9] and eczema [10, 11], more frequent acute respiratory illnesses [12, 13], and gastric illness [14].

Many ways of assessing indoor dampness quantitatively have been explored. These include measurements of mould spores or fragments, including ergosterol, endotoxin, ß (1→3)glucans, in air or settled dust. Dampness-related allergens such as house dust mite allergens have also been used. However, few of these have been consistently linked to health effects [1, 4, 15], unlike the aforementioned qualitative and semi-quantitative measures. Furthermore, these quantitative indicators frequently are not associated with other indicators such as visible mould, or with actual humidity levels [16-19].

This review focuses on the association between house characteristics and frequently used measures of indoor dampness, in order to contribute to identification of effective interventions to reduce indoor dampness and associated adverse health effects. The review focus is on qualitative assessments (and measured moisture) as these are the most consistently associated with measured health outcomes in epidemiological studies.

2.2 Methods

This review is restricted to English language journal articles published since 1970, accessed via Pubmed or web of science and for which the full paper could be obtained. A systematic approach was taken as illustrated in Figure 1. Studies were screened in order to include only those that reported an association between one (or more) of the selected dampness measures and one (or more) of the selected residential house or household characteristics. Where papers made a simple comparison between two or more groups a direction of effect was noted. Where studies reported an effect size derived using regression analysis, these were included in the reported results.

This review seeks to answer the following broad research question:

1 ***What is the current state of evidence of the association between house and household characteristics and common measures of indoor dampness in occupied houses.***

Other questions that are assessed to the extent that enough evidence was available include:

2 ***Are the assessments for house characteristics similar enough for comparison?***

3 ***Is there a general agreement across studies on the direction of the association between house characteristics and indoor dampness?***

For associations where the evidence was deemed sufficient, sensitivity testing of broader relationships was explored through asking:

4 ***Is agreement increased/decreased within subgroups of;***

4.1 ***Different dampness outcomes?***

4.2 ***Higher quality rated studies?***

4.3 ***Studies from within the same region?***

4.4 ***Studies using objective/inspected dampness vs subjective/self-reported dampness assessments?***

4.5 ***Studies assessing the associations using multivariate models adjusting for other house characteristics?***

2.2.1 Inclusion criteria: indoor dampness measures

As discussed above, papers were included that reported either actual moisture measurements in a residential setting (including relative humidity, absolute humidity, indoor/outdoor vapour pressure, moisture content of floors and wall surfaces or internal framing), or one of the following dampness indicators: visible mould, damp spots or patches, water damage, moisture stains including evidence of flooding or leaks, mouldy odour and condensation. Measures observed in the literature but not included due to being unique to one or two studies, include damp clothes or bedding (studies reporting this outcome generally also reported on at least one other of the selected measures and were typically included in this review). Where results were reported separately for visible mould (not part of an index or group of dampness outcomes assessed together) they are reported separately.

2.2.2 Inclusion criteria: house and household characteristics

Physical aspects of the house, such as age, materials, heating and ventilation systems, sun exposure directly on the house etc., are included if plausibly related to indoor dampness. Household characteristics associated with damp housing identified from previous literature were also included, such as number of occupants, tenure (owner occupied vs rented) and presence of pets. Types of residence were selected based on whether the study participant(s) was/were responsible (to any extent) for maintaining the indoor environmental quality (ie, they were responsible for heating and ventilation behaviours, as well as cleaning). It is by this reasoning that dorm rooms were included (they are essentially similar to a rented apartment) while rest-homes, offices and prisons were not. These criteria are summarised in Table 2.1. Exclusion criteria are stated for the sake of clarity.

Table 2.1 Inclusion and exclusion criteria

Inclusion criteria (meets all criteria below)	Exclusion
▪ Based on original research ▪ Published in peer-reviewed journal ▪ Full text available ▪ Paper in English language	▪ All other instances
Research conducted in: • House • Flat • Apartment • mobile home • student dorm *owned by the occupant or a public or private landlord*	▪ Rest home ▪ Office ▪ Prison ▪ managed residential setting (i.e. mental health residential facility)
Quantitative OR qualitative assessments of any of the following: ▪ Moisture or humidity indoors ▪ Moisture measurements in framing, subfloor or foundations ▪ visible mould ▪ visible damp patches ▪ water damage ▪ damp stains ▪ condensation ▪ musty or mouldy odour ▪ dampness index/dampness assessments made of the above measures grouped together	▪ Damp clothes or bedding ▪ stuffy odour ▪ other odours ▪ suspected moisture problem ▪ spore counts ▪ hyphal growth ▪ DNA based fungal analysis ▪ Other quantitative fungal assessments ▪ Modelled moisture
AND any of the following when associations were measured with moisture outcomes listed above: ▪ Physical house characteristics (including heating/ventilation systems and appliances/air change rate (airtightness)) ▪ climate factors ▪ tenure ▪ number of occupants or occupant density	▪ Urban-rural ▪ occupant behaviour (where not measured alongside physical parameters)

Where a study has indicated categories for answers to general questions such as “Type of house” or “Heating system” they are specified in the review. Otherwise definitions were not reported. Where ‘children’ or ‘adults’ were reported under the heading “number of houses”, it was not possible to determine whether each participant came from a separate household. In those cases, the number of children/adults is reported.

Figures for associations between house characteristics and dampness measures were reported if they reached statistical significance, p≤0.05, in regression analysis. In situations where the result was close to significance (p≤0.1), it is reported here as a non-significant (NS) result with a direction of effect noted. Where an association was neither significant, or close to significant, it is included in the tables as unassociated (denoted with ↔).

2.2.3 Search Process

Stage 1 of the search involved a search of Pubmed and Web of Science initially conducted in March 2017, and updated in March 2022. The following search terms were used in pairs with one from group one and one from group two:

Group 1. Home/Hous*/dwelling/indoor AND

Group 2. Damp*/Mould/ Mold/Moisture/Water damage/Mouldy odour/ moldy odor/musty odour/musty odor.

During this stage abstracts were screened for whether there was an apparent assessment of indoor dampness in a domestic setting.

Stage two involved downloading the full paper in order to read the methods. Methods checking involved looking at whether the study measured both one of the dampness outcomes of interest (see section above on inclusion criteria) and any kind of housing characteristic. Papers included after methods checking were checked for references to similar papers, and these papers were identified, downloaded, and had references checked iteratively. This search process is illustrated in in Figure 2.1.

2.2.4 Assessment of study quality

Included studies were assessed for quality according to a rating system, summarised in Table 2.2. Briefly, studies were allocated points up to a maximum of six points based on the assessment of the study design against the rating criteria. These rating criteria were derived to avail comparison of different types of studies, including observational and quasi-experimental studies. An arbitrary cut point of 150 houses sample size was selected for an additional point in the rating value, to reflect that results are to some degree generalisable, and sufficient for multivariate analysis. Since none of the studies included had the outcomes under review as their primary focus of the research, study quality was not expected to be generally high.

Table 2.2. Rating criteria

1.	Is the approach appropriate to answer the study question?	+1
2.	Are the data collection methods adequate to answer the study question? 1. Sample size sufficient (over 150 houses)? 2. Dampness assessment based on moisture measurements or inspection. 3. Longitudinal or before/after intervention design	 +1 +1 +1
3.	Are the findings adequately derived from the data (figures reported with significance testing)?	+1
4.	Is the interpretation of results substantiated by the data (reported figure adjusted for covariates)?	+1

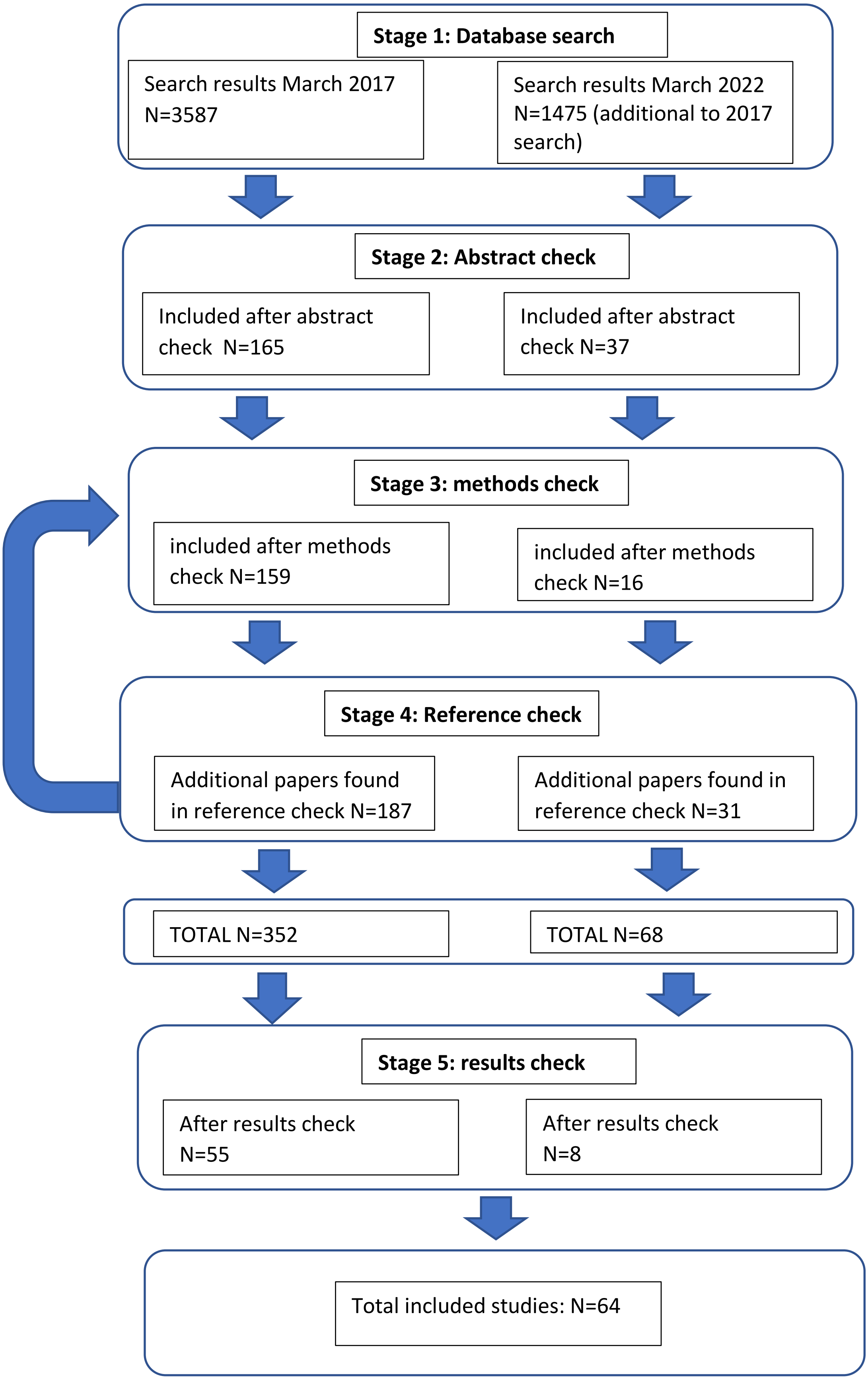
2.2.5 Organisation of themes

Themes were derived after the search process was completed. House characteristics were grouped together within themes when either where there were too few results to compare more specific characteristics (eg building envelope components), or where there was evidence (or a hypothesis under questions i.e building age and condition) to suggest that these characteristics act in similar ways (ie humidifiers and gas appliances are grouped together based on moisture production properties (WHO 2009b). Where enough papers reported associations on the same characteristic, these were not grouped into a theme (eg occupancy). In summary, characteristics have been grouped together to the least degree possible, to facilitate understanding of specific components. Each theme described in the review will be followed by a separate discussion section, and the synthesis of each of these discussion sections has been summarised in the conclusion section at the end of the review.

2.3 Results

The most commonly reported house characteristics were ventilation characteristics (34 studies) and building age or construction period (32 studies).

Figure 2.1: Search process and results



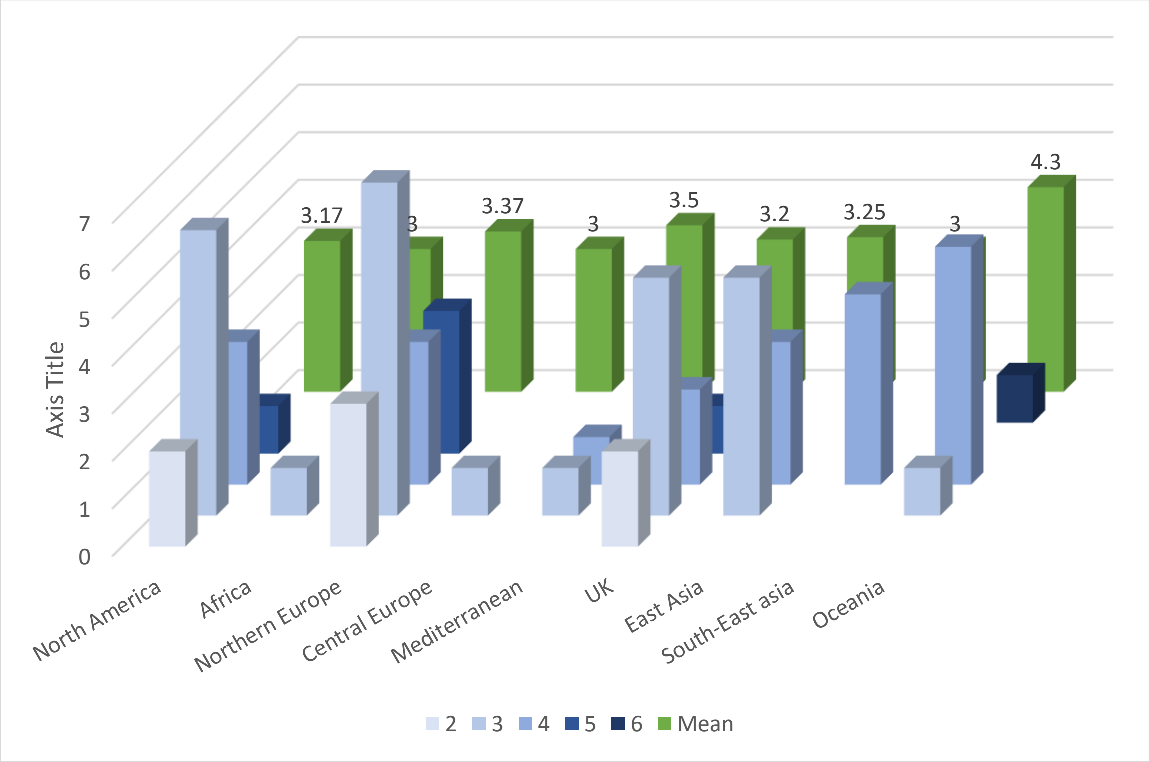
2.3.1 Study quality

In total, 64 studies were selected for inclusion in the review. Only one study was rated 6, the highest possible score, a randomised controlled intervention study from Oceania that included RH measurements before and after insulation installation. Studies rated with a score of 5 came from North America (1), Northern Europe (3) and the UK (1). The remainder of the studies scored between 2 and 4. Average score by region, and the number of studies for each score by region is presented in Figure 2.2. Some studies have been allocated two quality ratings, due to the reporting of different results differently (eg some results reported as comparison of means and others in regression analysis, or some as self-report and others based on inspection). Therefore, in the overview of study quality these are referred to by the highest rating; in the tables, individual ratings are provided according to the result being presented in each table. Ratings are not always discussed in the text, but in general, throughout the text, higher rated studies are emphasised more.

2.3.2 Study regions

Studies were grouped by region. These are based on the number of studies per region and, as far as possible, on similarity of construction style and climatic factors. For example, 29 included studies were from Europe, and this large number allowed for this group to be separated into climate groups (Northern Europe, Central Europe, Mediterranean and UK). On the other hand, studies from both the United States and Canada frequently assessed several geographically dispersed cities within the same study, meaning that it was not suitable to similarly break this group down further by climate, despite the wide range of climates within this region. A few differences were observed in study methods by region. Studies from Northern Europe were more likely to use inspector-assessed dampness assessments, while studies from East Asia were more likely to use self-reported assessments. Related to this, studies using inspected dampness and house characteristics typically had smaller sample sizes (less than 1000 houses), compared to those relying on surveys only. One exception was a high-rated study from the UK that used inspections, objective dampness measures, and had a sample size of over 3000 houses [24].

Figure 2.2. Study quality by region



2.3.3 Study Themes

One multi-centre study was unable to be sorted thematically, and this is not included in the thematic review. This paper had only one result related to the dampness outcomes under question, finding that having a bed in the living room was not associated with dampness outcomes [26]

2.3.4 Key for tables

	Number of houses	Reported associations	
RELATIVE HUMIDITY			Section shows house characteristics listed below here are associated with this moisture outcome
		vs terrace	Reference category used in analysis
		-detached ↔	Direction in which characteristic is associated with outcome ↑ = characteristic is associated with increase of outcome (here relative humidity) ↓ = characteristics is associated with a reduction of outcome (RH) ↔ = characteristic is not associated with moisture outcome
		OR 0.76 (0.58-1.01)	Where reported effects are statistically significant we include them here.

2.4 House type and size

2.4.1 House Type

There was reasonable consistency in how house type was assessed across the studies, though the main difference is where to draw the line along the spectrum from detached, semi-detached (two houses only conjoined), terraced, flat and apartment. Typically, these various types are grouped for analysis, and groupings differ, somewhat reducing comparability of results. Different terminology defining house types were used across studies. We have grouped these definitions as follows:

Detached also includes:

- “house”
- “single-family house”
- “bungalow”

Apartment also includes:

- “flat”
- “multi-family building”

Mobile home also includes:

- “trailer”

Terraced also includes:

- “chain house”
- “row house”

Four studies, from Northern Europe (2), the UK (1), and the Mediterranean (1), measured indoor relative humidity (RH) in relation to house type. Only one study found a relationship, with apartments more likely to be in the categories with highest average RH [27].

Six studies assessed visible mould levels according to type of house, from North America (1), the UK (2), East Asia (1) and Oceania (1) and one multi-centre study (1). In the UK detached houses were associated with a reduction in odds of inspector-observed mould (aOR 0.76 (0.58-1.01); Table 2.4), and flats were associated with an increased odds of inspector-observed mould (aOR 1.81(1.14-2.85), both compared to terraced houses [24]. These results were adjusted for house age, wall cladding type, presence of ceiling insulation, SAP rating (an energy efficiency rating derived from the UK House Condition survey) and deprivation quartile in a sub-sample of 1604 homes. A multi-centre study also found that detached houses were associated with less inspector-observed mould compared to apartments [28]. However, two studies using self-reported mould showed detached houses were associated with more visible mould (Table 2.4). The UK study by Sharpe et al., [47] found an increased odds of OR 2.3 (1.5-3.5) in semi-detached or detached houses, compared to all others; they also reported an OR of 1.9 (1.3-2.9) for a slightly different grouping described as “house” compared to all others. This analysis was adjusted for deprivation index and month of the year, and some house characteristics (glazing insulation and heating). A study from China, using self-reported mould, found no significant associations with house type in 2010, but in a 2019 survey they found detached houses had the least visible mould compared to apartments or “other” (aOR 0.25 (0.08-0.78); Table 2.4) [29].

Five studies from Northern Europe assessed house type in relation to visible signs of dampness, with two finding increased dampness in detached homes [22, 30], one of which adjusted for presence of a basement, renovation status and RH (aOR 3.61 (1.84-7.06), Table 2.4)[22]. Another two found the reverse; increased signs of damp in apartments compared to detached and semi-detached houses [31], and compared to detached houses [32]. Six studies from elsewhere in the world reported similarly conflicting results. For example, two large multi-centre studies, one from Europe and one from East Asia, both found less dampness in apartments [28, 33], but it should be noted that when the East Asia survey was repeated nine years later, this relationship was not apparent [33]. Further, the result for dampness was the opposite of what was found in the same study when looking at house type and visible mould (as described above, apartments in this study were associated with more visible mould, but less dampness, compared to detached houses)[33]. Another study in students' accommodation, found blocks with 2-11 “apartments” had more dampness and mould than either detached or larger apartment blocks in univariate regression analysis [34]. Contradictory findings are also reported between signs of dampness and mobile homes [35, 36](Table 2.4)

Similar contradictory results are demonstrated in the relationship between house type and condensation or mouldy odour (Table 2.4).

2.4.1.1 House level

Only two studies reported results on the association between floor-level of the home and dampness outcomes. One study, from the Mediterranean, found no association with moisture measurement (RH) [37]. However the same study found that houses on the top floor had increased risk of visible mould (they also had more houseplants on average) [37]. Another study, from East Asia grouped houses by ground-floor, top-floor and other floors, reported that homes on both the ground floor and the top floor were at increased risk of signs of indoor dampness (*vs other levels*; aORs for *ground-level* 2.16 (1.77-2.62), and *top-level* 1.40 (1.19-1.65); Table 2.4), but reduced risk of condensation (*vs other levels*; aORs for *ground-level* 0.8 (0.68-0.97), and *top-level* 0.81 (0.70-0.93); Table 2.4) [38]

Table 2.4. House type

STUDY	Number of houses	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
2005 Hesselmar et al. Sweden [44]	109	Measurement	vs living in a house, -flat ↔	Chi-squared	3
2006 Oreszczyn et al. UK [24]	3099	Measurement	vs living in a terraced house -detached ↔ -flat ↔	Multivariate regression	5
2006 Ceylan et al. Turkey [37]	242	Measurement	vs other -flat ↔ Vs any other floor -house on top floor ↔	Comparison of means	3
2021 Psomas. Sweden [27]	1400	Measurement	Vs detached -apartment ↑	Comparison of means	3
VISIBLE MOULD					
1989 Brunekreef et al. USA [58]	4625*	Self-report	-detached houses ↑	Comparison of means.	2
2005 Howden-Chapman P et al New Zealand [41]	613	Self-report	Vs detached -apartment ↑	Univariate regression	4
2006 Oreszczyn et al. UK [24]	3099	Inspection	vs terrace -detached↓ OR 0.76 (0.58-1.01) -flat ↑ OR 1.8 (1.14-2.85)	Multivariate regression	5
2006 Ceylan et al. Turkey [37]	242	Inspection	-top floor apartment ↑ Vs any other floor -house on top floor ↔ Top floor had more plants	Comparison of means	4
2015a Sharpe et al. UK [47]	671	Self-report	vs other -detached/semi-detached ↑ OR 2.3 (1.5-3.5)	Multivariate regression	4
2015 Liu et al. China [38]	15 266*	Self-report	vs other -ground floor level ↑ aOR 2.30 (1.79-2.07) -top floor level ↑ aOR 1.37 (1.08-1.72)	Multivariate regression	4
2017 Norback et al. Europe [28]	subsample of 3118 inspected	inspection	-apartment ↔ -detached ↓ -converted apartment↑	Comparison of means (stratified by size and type of house)	3
2020 Cai et al. China [29]	8947	Self-report	**(child's bedroom 2010)** vs apartment -detached ↔ **(child's bedroom 2019)** Vs apartment -detached ↓ OR 0.25 (0.08-0.78)	Multivariate regression	4
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1994 Spengler J. et al USA & Canada [36]	12842*	Self-report	-Mobile homes ↓	Multivariate regression (data not shown)	3
1996 Pirhonen I. et al. Finland [68]	1460*	Self-report	-detached house ↔	Comparison of means	3
2001 Kipelnäinen et al. Finland [30]	10667*	Self-report	-detached & terrace ↑	Comparison of means	2
2006 Haverinen-Shaughnessy et al. Finland [22]	363	Inspection	vs apartment -detached & terrace↑ OR 3.61 (1.84-7.06)	Multivariate regression	5
2006 Gunnbjornsottir et al. Iceland, Norway, Sweden, Denmark, Estonia [32]	16190	Self-report	-apartment ↑ -detached house ↓	Comparison of means	3

2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	-multi-family home ↑	Chi-squared	4
2013 Sun & Sundell. USA [35]	2819*	Self-report	-trailer ↑ -apartment ↑ -detached ↓	Chi-squared	4
2014 Choi et al. South Korea [61]	2740*	Self-report	-apartment ↓	Chi-squared	3
2014. Takaoka et al. Japan [48]	1048*	Self-report	-apartment ↓	Chi-squared	3
2015 Liu et al. China [38]	15 266*	Self-report	vs other -ground floor level ↑ aOR 2.16 (1.77-2.62) -top floor level ↑ aOR 1.40 (1.19-1.65)	Multivariate regression	4
2016 Lanthier-Veilleux, Genereux & Baron, Canada [34]	2097*	Self-report	Vs detached -block of 2-11 flats ↑ OR 1.48 (1.19-1.84) -block of 12+ apartments ↔	Univariate regression	3
2017 Norback et al. Europe [28]	7127 [with subsample of 3118 inspected	Self-report and inspection	-apartment ↓ -detached & converted ↑	Comparison of means (stratified by size and type of house)	4
2020 Cai et al. China [29]	8947	Self-report	**(2010)** Vs apartment -detached↑ OR 1.60 (1.25-2.05) **(2019)** Vs apartment -detached ↔	Multivariate regression	4
CONDENSATION					
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	-detached ↑	Chi-squared	4
2013 Sun & Sundell. USA [11]	2819*	Self-report	-trailer ↑	Chi-squared	4
2014 Choi et al. South Korea [61]	2740*	Self-report	-apartment ↓	Chi-squared	3
2015 Liu et al. China [38]	15 266*	Self-report	vs detached house -apartment ↑ aOR 1.48 (1.28-1.71) -ground floor level ↓ aOR 0.81 (0.68-0.97) -top floor level ↓ aOR 0.81 (0.70-0.93)	Multivariate regression	4
2016 Thacher et al. Sweden [6]	3798*	Self-report	-type of house ↔	Chi-squared	3
2016. Takaoka et al. Japan [48]	1048*	Self-report	-apartment ↑	Chi-squared	3
2020 Cai et al. China [29]	8947	Self-report	**(2010)** Vs apartment -detached↓ OR 0.62 (0.53-0.72) -other ↓ OR 0.55 (0.46-0.67) **(2019)** Vs apartment -detached ↔ -other ↔	Multivariate regression	4
MOULDY ODOUR					
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	-apartment ↑	Chi-squared	4
2016. Takaoka et al. Japan [48]	1048*	Self-report	-apartment ↔	Chi-squared	3
2020 Cai et al. China [29]	8947	Self-report	**(2010)** Vs apartment -detached ↑ 1.42 (1.14-1.77) **(2019)** Vs apartment -detached ↔	Multivariate regression	4

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

House size

Number of rooms and number of bedrooms were included in this category as proxy measures of house size. There was less consistency, and therefore comparability in the size assessments, across studies, than for house type assessments.

Two studies reported relative humidity measurements in relation to house size. One from Northern Europe that found that larger houses had higher RH [27], and the other, from Africa, finding that houses with more rooms (a proxy for size) had lower RH [39].

Five studies, from East Asia (2), Northern Europe (1), Oceania (1) and North America (1), reported on the relationship between visible mould indoors and size of the home. Two large studies, from East Asia reported that larger homes were associated with less visible mould. Liu et al found reduced odds of self-reported visible mould for houses larger than $150m^2$, compared to those $40m^2$ or smaller (aOR 0.50 (0.29-0.87); Table 2.5) while homes 41 to $150m^2$ were not associated with a statistically significant increase using multivariate analysis adjusted for other house characteristics [38]. The study by Cai et al, which included two repeats of the same survey (in 2010 and 2019) also reported that larger homes had a lower risk of visible mould using the same categorisation (*vs* $60m^2$ *and smaller*, aORs for; *61 to* $100m^2$ 0.56 (0.41-0.76), and *larger than* $100m^2$ 0.68 (0.48-0.95); Table 2.5); however in the 2019 survey, although the odds were reduced, these results were not statistically significant (data not shown). Two more studies, from Northern Europe (1) and Oceania (1), reported the reverse, i.e. they found that larger houses were associated with an increased likelihood of inspector-assessed [40], and self-reported visible mould (*vs 0-2 bedrooms*, ORs for *3 bedrooms* 1.88 (1.28-2.77), and *4 or more bedrooms* 2.03 (1.50-2.73); Table 2.5) [41]. A study from

North America reported no association between house size and likelihood of inspector-assessed visible mould [21].

Signs of dampness indoors were assessed by two studies from Northern Europe (1), and East Asia (1). In Northern Europe, larger homes were related to increased risk of dampness [22], while in East Asia, larger homes were associated with less indoor dampness (*vs 60m^2 and smaller*, aORs for; *61 to 100m^2* 0.58 (0.42-0.81), and *larger than 100m^2* 0.43 (0.27-0.69), Table 2.5) [29], converse to the results reported for visible mould, these reductions in risk were significant in the 2019 survey but not in 2010 (data not shown)(Table 2.5).

Two studies also assessed signs of dampness in relation to overall building (rather than house) size. A multi-centre study from throughout Europe reported that buildings with two to four families were at higher risk of signs of both self-assessed, and inspector-assessed signs of dampness, compared to either detached or larger buildings [28](Table 2.5). Similarly, a study from North America reported similar findings using univariate regression (*vs detached* ORs for *2-11 apartments* 1.48 (1.19-1.84), *12 or more apartments* not associated; Table 2.5) [34].

Two studies reported on house size in relation to self-reported condensation, both from East Asia, one using multiple regression, adjusting for other house characteristics. Of these two studies, one, using univariate analysis, found that larger homes were associated with increased risk of condensation in 2010 (*vs 60m^2 and smaller*, aORs for; *61 to 100m^2* 1.43 (1.21-1.68), and *larger than 100m^2* 1.69 (1.41-2.03); Table 2.5); however, these associations were not apparent when the survey was repeated in 2019

[29]. The other study, also from China, reported no significant association with house size in multivariate analysis [38].

Three studies reported on associations with mouldy odour, from East Asia (2), and North America (1). Liu et al considered five size increments, with the reference category as 40m^2 or smaller; this study found no relationship for homes 41-75m^2, but it did find a significant reduction in odds of mouldy odour in homes 76-100m^2 (aOR 0.76 (0.59-0.98); Table 2.5), and 101-150m^2 (aOR 0.68 (0.51-0.91); Table 2.5), while houses over 150m^2 in size were not associated with mouldy odour (data not shown) [38]. Also reporting results from East Asia, Cai et al., found significant reductions in risk of mouldy odour in both iterations of the survey, conducted in 2010 and 2019 for houses larger than 60m^2 (Table 2.5), but the association was not significant when adjusted for other covariates in multivariate analysis [29]. Finally, a study from North America, looking at the same relationship, found no association between house size and likelihood of mouldy odour also adjusting for other house characteristics in multivariate regression [42].

Table 2.5. House size

STUDY.	Number of houses	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
2021 Psomas. Sweden. [27]	1400	Measurement	-larger houses ↑	Comparison of means	3
2016. Fakunle et al. Nigeria [39]	132	Measurement	-number of rooms ↓	Spearman's corelations	3
VISIBLE MOULD					
1999 Koskinen et al. Finland [40]	310	Inspection & self-report	-larger houses ↑	t-test comparison of means.	4
2005 Howden-Chapman et al New Zealand [41]	613	Self-report	Vs 0-2 bedrooms -3 bedrooms ↑ OR 1.88 (1.28-2.77) - ≥4 bedrooms ↑ OR 2.03 (1.50-2.73)	Univariate regression	4
2010 Dales et al. Canada [21]	357	Inspection	-size of house ↔	Chi-squared	3
2015 Liu et al. China [38]	15 266*	Self-report	-vs house 40m^2 or smaller 41-150 m^2 ↔ >150 m^2 ↓ aOR 0.50 (0.29-0.87)	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**(child's bedroom 2010)** Vs ≤60m^2 -61-100 m^2 ↓ OR 0.56 (0.41-0.76) ->100 m^2 ↓ OR 0.68 (0.48-0.95) **(child's bedroom 2019)** Vs ≤60m^2 -61-100 m^2 ↔ ->100 m^2 ↔ (non-significant reductions)	Univariate regression	4
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
2006 Haverinen-Shaughnessy et al. Finland [22]	363	Inspection	-larger house ↑	Comparison of means	5
2016 Lanthier-Veilleux, Genereux & Baron Canada [34]	2097 Students	Self-report	Vs detached -2 to 11 apartments OR 1.48 (1.19-1.84) -12 apartments or more ↔	Univariate regression	3
2017 Norback et al. Europe [28]	7127 [with subsample of 3118 inspected	Self-report and inspection	building size (2-4 families) ↑	Comparison of means (stratified by size and type of house)	4
2020 Cai et al. China [29]	8947	Self-report	**Univariate (2010)** Vs ≤60m^2 -61-100 m^2 ↔ ->100 m^2 ↔ (non-significant reductions) **(2019)** Vs ≤60m^2 -61-100 m^2 ↓ aOR 0.58 (0.42-0.81) ->100 m^2 ↓ aOR 0.43 (0.27-0.69) **Multivariate** Vs ≤60m^2 -61-100 m^2 ↔ ->100 m^2 aOR 0.44 (0.25-0.78)	Univariate and multivariate regression	4

CONDENSATION					
2015 Liu et al. China [38]	15 266*	Self-report	vs house 40m^2 or smaller 41-75m^2 ↔ 76-100m^2 ↔ 101-150m^2 ↔ >150m^2 ↔	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**(2010)** Vs ≤60m^2 -61-100 m^2 ↑ aOR 1.43 (1.21-1.68) ->100 m^2 ↑ aOR 1.69 (1.41-2.03) **(2019)** Vs ≤60m^2 -61-100 m^2 ↔ ->100 m^2 ↔	Univariate regression	4
MOULDY ODOUR					
2015 Liu et al. China [38]	15 266*	Self-report	vs house 40m^2 or smaller 41-75m^2 ↔ NS 76-100m^2 ↓ aOR 0.76 (0.59-0.98) 101-150m^2 ↓ aOR 0.68 (0.51-0.91) >150m^2 ↔ NS	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**Univariate** **(2010)** Vs ≤60m^2 -61-100 m^2↓ aOR 0.52 (0.42-0.66) ->100 m^2↓ aOR 0.57 (0.44-0.73) **(2019)** Vs ≤60m^2 -61-100 m^2↓ aOR 0.62 (0.46-0.85) ->100 m^2↓ aOR 0.64 (0.43-0.96) **Multivariate** Vs ≤60m^2 -61-100 m^2 ↔ ->100 m^2 ↔	Univariate and multivariate regression	4
2022 Sun et al. Canada [42]	199	Self-report	-House size ↔	Multivariate regression	4

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.4.2 Discussion: House type and size

It would appear, that despite type of house being one of the most frequently reported (assessed) house characteristics in relation to indoor dampness, there is very little ability to draw any type of consensus between studies, with almost equal numbers showing each house type associated with both more frequent and less frequent dampness or mould. This lack of a consisten relationship holds true when looking at objective measures only, those studies rated 4 or higher only and even when comparing the large number of studies from a similar climate area (northern Europe). In summary, it appears that type of house by itself can tell us little about indoor dampness risk. There are differences, regionally, in the socio-economic status of inhabitants of detached dwellings. In East Asia, detached dwellings may be occupied by lower-income families [43], while the reverse may often be true in Europe [31] and North America. This means that there may be confounding by socio-economic status (SES). Also, detached houses are likely to be larger than apartments, particularly in those areas where detached houses are linked with affluence. Future studies working to improve in this area, should assess house size and socio-economic status, and use both in multivariate analysis to assess this relationship.

When looking at house size, the story is fairly similar, although there is the appearance that the results are more consistent when grouped by climate region, with colder climates finding more dampness in larger houses, and warmer climates finding more dampness in smaller houses.

Four of the studies included here reported results mutually adjusted for house type and house size in multivariate analysis. A study from Oceania found both measures significantly associated in univariate analysis, while in mutually adjusted multivariate regression, including other house and climate characteristics, neither of these measures remained independently associated with self-reported visible mould [41]. Another study from Northern Europe, in mutually adjusted analysis, found that detached/terraced houses were significantly associated with increased signs of inspector-assessed dampness but not house size [22]. A third study from East Asia, which tested both characteristics in multivariate regression analysis, found that larger houses had independently lower odds of musty odour (house type unassociated), and apartments were independently associated with more condensation (house size unassociated)[38]. The last study reported associations between larger houses and increases in several dampness indicators in univariate analysis (visible mould, condensation, water damage and mouldy odour), however, in mutually adjusted analysis, only the association with water damage (reduced risk in larger homes) remained statistically significant [29].

The sample reported on here in relation to house-type, by Hagerhed-Engman et al, was included in another study, where house type was stratified according to rural, suburban or urban location showing that few (5.2%) multi-family houses (apartment blocks or blocks of flats) were located rurally, while few detached homes (3.5%) were located in urban centres, with both types present in suburban locations at approximately similar levels. This study also showed that detached houses in the sample were on average, older [10]. So, this shows that house type may often be correlated with other, potentially confounding, characteristics.

In conclusion, the type of house or building does not appear to be an independent predictor of indoor dampness conditions. House level, on the other hand, does appear to be an independent predictor, with both ground floor and top-floor apartments more likely to experience dampness, although the evidence for this is relatively weak..

2.5 Construction factors

2.5.1 External construction factors

2.5.1.1 Subfloors, basements and foundations

Seven studies, from Northern Europe (4), North America (2) and one multi-centre study, (1) assessed dampness in houses in relation to basements and foundation type. Two of these, both from Northern Europe, compared moisture measurements in houses with and without a basement. The first reported no difference in internal RH levels [44], and the other reported that moisture content (MC) >14%, measured in foundations, was most common in houses with a crawl space (76%) followed by homes with a basement (61%), and lastly those with concrete slab foundations (40%) [45]. This study also reported that mouldy odour was more prevalent in homes with higher measured moisture in foundations (14.9% of homes with foundation MC>14% had mouldy odour compared with 4.4% of homes with measured moisture ≤14%) [45]. A third study from Northern Europe, based on inspector-assessed signs of dampness, found that both houses with piles and those with a basement (vs those built on concrete slab foundations) were more likely to have indoor dampness, but in multivariate analysis only the association with basements continued to show an effect, but this was not statistically significant [22]. A fourth study from Northern Europe assessed foundation type in detached houses, and found that there were no significant associations, in multivariate regression adjusted for other house characteristics, with visible dampness, condensation or mouldy odour. However, the authors reported floor moisture was more common in houses with a concrete slab, compared to houses with a basement or built on piles [31]. The reverse (albeit, of dampness measured in foundations rather than floors) was reported by Wang et al., 2017, although it should be noted that Wang et al., separated out insulated vs non-insulated concrete slabs, demonstrating less dampness in the foundations where insulation was placed below the slab (60% without below-slab insulation had foundation MC over 14%, compared with only 7% of those where the slab was insulated from the ground) [45].

A multi-centre study from 18 different countries showed that self-reported visible mould was increased in homes with basements rated as wet (OR 2.10 (1.64-2.68); Table 2.6), as well as those with a basement rated dry, (OR 1.24 (1.07, 1.44) Table 2.6) compared to homes without a basement [46]. Finally, in relation to basements, a study from North America reported on homes with a bedroom in the basement. This study showed that a bedroom in the basement was positively associated with indoor signs of dampness and mould (OR 1.53 (1.21-1.93)[34].

The second study from North America reported that homes built on piles were associated with increased odds of four different self-reported measures of indoor dampness (damp or mould spots OR 1.75 (1.05, 1.95), floor moisture OR 1.51 (1.06, 2.13), condensation OR 1.80 (1.40, 2.31)) and suspected moisture problem (OR 1.59 (1.12, 2.24); Table 2.6). These analyses were adjusted for house age and type [35].

2.5.1.2 Framing, and walls

Four studies assessed walls or framing type, from the UK (2), Northern Europe (1) and East Asia (1). One study from the UK reported the association between wall type (solid or concrete vs cavity) and measured moisture (RH), which showed that homes with cavity walls had lower average RH (1.6% on average) compared to those with solid brick or concrete walls [24]. The second UK study found homes with external walls constructed of brick, had higher odds of indoor visible mould compared to any other construction type (OR 1.7 (0.9, 3.1); univariate data not shown in table), although this result was not significant in multivariate analysis [47] after adjustment for deprivation, heating, insulation and glazing characteristics. The study from Northern Europe reported that homes constructed with a wooden frame were more likely to be characterised as damp by an inspector (aOR 1.69 (1.02, 2.81) Table 2.6) [22]. The study from East Asia found that “wooden houses” were associated with increased self-reported water leakage (OR 2.4 (1.5, 3.8)) but not with mouldy odour; it was also associated with less condensation on windows (OR 0.74 (0.56, 0.98) Table 2.6) [48].

2.5.1.3 Windows

Please note that glazing type (single double etc), will be dealt with in section 2.13 on insulation.

Five studies assessed window type, from East Asia (3) and Northern America (2) and two studies assessed the number of windows per room (Africa (1)) or proportion of window area to heating area (Northern Europe (1)). One study from East Asia, reported that window type was not associated with signs of dampness indoors or condensation (Table 2.6) [43]. The two studies looking at associations with objective measurements (RH) both reported on window area (per room/heated area). The study from Africa found that proportionally more windows was associated with reduced RH [39], while the study form Northern Europe found no relationship between window area proportionally to the heated area, and RH [27].

Of the studies that assessed associations between window type and dampness outcomes, all reported on associations with condensation, using multivariate regression analysis adjusted for other house characteristics. All three studies found that wooden framed windows were associated with less condensation. PVC window frames were positively associated with condensation in East Asia (OR 1.80 (1.42, 2.28) Table 2.6), compared to windows with wooden frames [49]. Aluminium windows were associated with more window condensation in North America (OR 1.28 (1.03, 1.59) Table 2.6) [11] compared with wooden frames, and in another study from East Asia, wooden frames were associated with reduced odds of condensation (OR 0.73 (0.60, 0.88), but with increased likelihood of mouldy odour (OR 1.36 (1.09, 1.70) Table 2.6) [38].

Another study from North America looked at window type in relation to mouldy odour. This study showed that in one of the four study regions (Halifax) the presence of wooden window frames was associated with a reduced probability of mouldy odour (26% probability), while in the other three regions, no association was found [42].

2.5.1.4 Sun vs shade on house

Three studies (from the Mediterranean (1) and Oceania (2)) reported the association of visible mould with shade or sun onto the house. One of these (Oceania) relied on self-reports, with the other two studies having mould assessed by inspectors. All three were similarly rated for quality (rating = 4). The study from the Mediterranean found that increased sunlight was associated with a reduced likelihood of observing visible mould [37]. Similarly, one study from Oceania reported that houses in shade all or most of the time, vs not, were more likely to have visible mould (aOR 2.46 (1.15, 2.68); Table 2.6) even after adjusting for other characteristics [41]; in contrast the third study, also from Oceania, found no associations with visible mould or with a subjective “feeling” of indoor dampness [50].

2.5.1.5 Roof

Three studies, all from Northern Europe assessed whether indoor dampness, one relying on self-reports and two others using inspector-assessed observations, was different in houses with flat roofs compared to others. All three reported increased odds of indoor dampness with flat roofs, with the highest quality-rated study showing an aOR of 1.69 (1.02, 2.81; Table 2.6), although the only other house characteristics this was adjusted for was presence of pets and number of siblings (a proxies for ventilation behaviours and number occupants respectively) [22]. The other study, which used self-reported visible mould, stratified results by house type (detached/apartment) and found an OR of 3.89 (1.76-8.55) in detached houses; they also reported an OR of 2.03 (1.42-4.08; Table 2.6) for flat roofs and mouldy odour [31]. In a study from Northern Europe, the impact of both roof geometry, and who built the roof was assessed in relation to whether the roof leaked. The authors reported leaks significantly more frequently in houses with flat or shed (mono-pitched) roofs, compared with hipped or gabled roofs, but also reported that these leaks generally caused only minor damage. The study also found that there were significantly fewer leaks in houses where the roof was constructed by the owner, compared to ones built by a construction company or contractors [51].

Table 2.6 External construction factors

STUDY	Number of houses	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
2005 Hesselmar et al. Sweden [44]	109	Measurement	-presence of a basement ↔	Comparison of means	3
2006 Oreszczyn et al. UK [24]	3099	Measurement	Vs solid/concrete -cavity walls ↓ -1.60% (-2.81, 0.4)	X^2	4
2006 Ceylan et al. Turkey [37]	242	Measurement	-increased sunlight into house ↓	Comparison of means	4
2016 Fakunle et al. Nigeria [39]	132	Measurement	-increased windows per room ↓	Spearman's corelations	3
2021 Psomas. Sweden. [27]	1400	Measurement	-window area (proportion) ↔	Comparison of means	3
MOISTURE CONTENT					
2017 Wang et al. Sweden [45]	605	Measurement	**Moisture content >14%** Vs concrete slab -basement present↑ -pile and bearer foundations ↑	Comparison of means	5
VISIBLE MOULD					
2002 Zock J-P et al 18 countries [46]	19 218*	Self-report	-presence of a basement ↑ Vs no basement -House with dry basement ↑ OR 1.24 (1.07-1.44) -House with wet basement ↑ OR 2.10 (1.64-2.68)	Multivariate regression	4
2005 Howden-Chapman P et al New Zealand [41]	613	Self-report	-sun on house; 'little' vs other ↑ OR 2.46 (1.15-5.27)	Multivariate regression	4
2006 Ceylan et al. Turkey [37]	242	Inspection	-increased sun into house ↔	Comparison of means	4
2012 Keall et al. New Zealand [50]	891	Inspection	-house in shade: a lot/a little ↔	Pearson's correlation coefficient	4
2015a Sharpe et al. UK [47]	671	Self-report and public records	-wall (external) constructed from brick ↑	Multivariate regression	4
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1998 Nevalainen et al. Finland [51]	450	Inspection	-Flat roofs ↑	Comparison of means	3
2006 Haverinen-Shaughnessy et al. Finland [22]	363	Inspection	-basement present ↑ -flat roof ↑ -timber frame ↑ OR 1.69 (1.02-2.81)	Multivariate regression	5
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	Vs gable roof -flat roof ↑ OR 3.89 (1.76-8.55) - foundation type ↔	X^2 for all data And Multivariate regression for single family houses only	4
2009 Sun et al. China [49]	115	Self-report	Vs wooden windows -PVC windows ↓ OR 0.51 (0.36-0.73)	Multivariate regression	3
2012 Keall et al. New Zealand [60]	891	Inspection	-house in shade: a lot/a little ↔	Pearson's correlation coefficient	4
2013 Sun & Sundell. USA [35]	2819*	Self-report	Vs concrete slab -foundation pile & bearer ↑ aOR 1.75(1.29-2.38) vs wood -aluminium window ↑ aOR 1.43 (1.05-1.95)	Pearson X^2 and p values And Multivariate regression Adjusted for house type and age	4
2014. Takaoka et al. Japan [48]	1048*	Self-report	(water leakage) Vs concrete -Wooden house ↑ OR 2.40 (1.5-3.8)	X^2	3
2016 Lanthier-Veilleux, Genereux & Baron Canada [34]	2097 Students	Self-report	-bedroom in basement ↑ OR 1.53 (1.21-1.93)	Univariate regression	1
2019 Kong et al. China [43]	7865	Self-report	-window type ↔	Multivariate regression	4

FLOOR MOISTURE					
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	VS crawlspace -concrete slab foundation ↑ 1.69 (1.18-2.04) Vs gable roof -flat roof ↑ OR 2.00 (1.19, 3.34) -foundation type ↔	Multivariate regression for single family houses only	4
2013 Sun & Sundell. USA [35]	2819*	Self-report	Vs concrete slab -foundation pile & bearer ↑ OR 1.51 (1.06-2.13) -flat roof (vs gable) ↑ OR 1.62 (1.07-2.43)	Pearson X^2 and p values And Multivariate regression	4
2014 Choi et al. South Korea [61]	2740*	Self-report	-balcony expansion ↑	X^2	3
CONDENSATION					
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	-roof type ↔ -foundation type ↔	X^2 for all data And Multivariate regression for single family houses only	3
2009 Sun et al. China [49]	115	Self-report	Vs wooden windows -PVC windows ↑ OR 1.80 (1.42, 2.28) -Iron windows NS	Multivariate regression	3
2013 Sun & Sundell. USA [35]	2819*	Self-report	Vs concrete slab -foundation pile & bearer ↑ OR 1.80 (1.40-2.31) Vs wooden window frames -aluminium windows ↑ OR 1.28 (1.03-1.59)	Pearson X^2 and p values And Multivariate regression	4
2015 Liu et al. China [38]	15 266*	Self-report	-wooden window frames ↓ OR 0.73 (0.60-0.88)	Multivariate regression & X^2	4 & 3
2014. Takaoka et al. Japan [48]	1048*	Self-report	Vs concrete -Wooden house ↓ OR 0.74 (0.56-0.98)	X^2	3
2019 Kong et al. China [43]	7865	Self-report	-window type ↔	Multivariate regression	4
MOULDY ODOUR					
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	Vs gable roof -flat roof ↑ OR 2.03 (1.42, 4.08) -foundation type ↔	X^2 for all data And Multivariate regression for single family houses only	3
2015 Liu et al. China [38]	15 266*	Self-report	-wooden window frames ↑ OR 1.36 (1.09-1.70)	Multivariate regression	4
2016. Takaoka et al. Japan [48]	1048*	Self-report	Vs concrete -Wooden house ↔	X^2	3
2017 Wang et al. Sweden [45]	605	Measurement	Foundation MC% >14% ↑	Comparison of means	5
2019 Kong et al. China [43]	7865	Self-report	-window type ↔	Multivariate regression	4
2022 Sun et al. Canada [42]	199	Self-report	wooden frame windows -Halifax ↓ 26% (12-49) -Edmonton ↔ -Montreal ↔ -Windsor ↔	Multivariate regression (Probability %)	4

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.5.2 Construction factors – Internal

2.5.2.1 Wall surface materials

Three studies reported associations of internal wall surface materials and dampness assessments, from East Asia (2) and North America (1). In analyses adjusting for other house characteristics, Liu et al. found that wallpaper was related to less frequent reporting of visible damp stains (aOR 0.65 (0.49-0.86)) and condensation (aOR 0.49 (0.28-0.85); Table 2.7) in the child's room, when latex paint was the reference. However, it was not associated with visible mould (Table 2.7) [38]. When each of the wall material categories were included as a separate category in the model (with latex paint as the reference), all of them except cement were associated with reduced odds of condensation (data not shown), thus suggesting latex paint and cement walls were associated with damp stains and condensation, but not visible mould. In agreement with these findings, another large study from East Asia in 2010, using univariate regression to test associations between dampness outcomes and house characteristics, and also using latex paint as the reference category, found that lime or cement wall linings were associated with increased visible damp stains (OR 2.16 (1.68-2.76) Table 2.7), with a similar result in 2019 (OR 1.73 (0.98-3.05), P=0.057; data not shown in the Table). Also in agreement with the previous study, the same characteristics (cement or lime wall linings) were not associated with visible mould, but in this case, they were associated with reduced odds of condensation (OR 0.58 (0.49-0.69); Table 2.7) although this was not statistically significant in the 2019 survey. None of these characteristics were independently associated in multivariate analysis, after adjusting for other house characteristics [29]. A study assessing wall linings in North America reported that drywall (presumably painted) was associated with reduced odds of floor moisture (aOR

0.58 (0.33-0.99) Table 2.7), but not associated with visible mould or condensation (adjusted for house type and age) [35].

2.5.2.2 *Flooring materials*

Carpets and other flooring materials were reported in relation to dampness outcomes in eleven studies, from North America (3), South-East Asia (2), East Asia (1), Oceania (1) Northern Europe (1), the UK (1), the Mediterranean (1) and Oceania (1). Ten of these reported on outcomes related to carpets specifically. Two studies assessed objective moisture measurements. One of these, from the Mediterranean reported no association between the presence of carpets and relative humidity [37]. Another study, from Oceania, that measured moisture inside a child's bed, reported higher measured moisture in beds in homes with carpets more than one year old [52]. Two studies focused on visible mould also reported no association with carpets in the UK [47], and East Asia [38]. In three studies, from South-East Asia (2), and North America (1), carpets were related with increased likelihood of indoor dampness [34, 53, 54], the most recent of these studies reported an OR of 1.51 (1.18-2.00) in univariate regression (Table 2.7), compared to houses without carpets [34]. On the other hand, two studies (one each from South-East and East Asia) reported no association between presence of carpets and signs of damp [38, 55], including one large study which assessed the association in multivariate analysis adjusting for other floor coverings and multiple other house characteristics (including ventilation patterns) [38]. Two studies, from East Asia (1), and North America (1), reported no association with condensation [35, 38].

Other flooring materials were assessed in a large study from East Asia, which measured self-reported dampness outcomes and adjusted analyses for other house characteristics. Tile, stone or cement floorings were consistently (in the 2010 and 2019 repeat surveys) associated with reduced condensation compared to laminate wood (aOR 0.58 (0.49-0.69) Table 2.7), but with increased damp stains and visible mould spots (although these latter results were not consistent in the repeat surveys) [29]. In another large study from East Asia, where solid wood flooring was used as the reference, the researchers reported that laminate wood was associated with increased visible mould (*Vs solid wood;* aOR 1.31 (1.04-1.64), Table 2.7) but it was not associated with visible damp stains or condensation [38]. A third study from North America, which also used wooden floors as the reference category, found that PVC flooring was associated with more condensation, but not with visible mould or signs of dampness [35].

2.5.2.3 Renovation and redecoration

Three studies assessed dampness outcomes in relation to recent redecoration or renovation, from East Asia (2) and Northern Europe. A large study from East Asia, which used multivariate regression analysis to test this relationship, found that redecorating within the past 12 months of the survey was associated with large increases in odds of water damage (aOR 3.1 (1.8-5.2), 2019 only), signs of dampness in the child's bedroom (aOR 3.52 (1.82-6.83)) and mouldy odour, (aOR 2.8 (1.2-2.4); Table 2.7). They concluded that these results were likely evidence of reverse causation i.e., the redecoration was likely the result of the dampness rather than the cause [29]. Another study from East Asia found that painting and new flooring in the past 12 months was not associated with condensation and mouldy odour, but it was strongly associated with water leakage in univariate regression (OR4.07 (1.99-8.34) Table 2.7), while painting was not associated with water damage. [48]. Finally, a study from Northern Europe showed that plumbing renovations were associated with more inspector-observed signs of dampness in multivariate analysis that adjusted for other house characteristics [22].

Table 2.7 Internal construction factors

STUDY	NUMBER	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
2006 Ceylan et al. Turkey [37]	242	Inspection	-wall to wall carpet ↔	Comparison of means	4
MISTURE CONTENT (bed)					
1997 Wickens et al New Zealand [52]	474*	self-report	-carpet more than 1 year old ↑	Univariate regression	4
VISIBLE MOULD					
2015 Liu et al. China [38]	15 266*	Self-report	Vs latex paint -wallpaper ↔ Vs solid wood -Carpet ↔ -laminate wood ↑ aOR 1.31 (1.04-1.64)	Multivariate regression	4
2015a Sharpe et al. UK [47]	671	self-report and public records	-carpet (> 2 rooms) ↔	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	-redecorated in last year ↑ OR 3.4 (2.2-5.3) 2019 only **Childs's bedroom (2010)** Vs laminate wood -Floor tile stone or cement ↑ OR 0.6 (0.4-1.0) -Flooring "other" ↔ -Walls ↔ **Childs's bedroom (2019)** Vs laminate wood -Flooring "other" ↓ OR 0.45 (0.25-0.80) -Wall coverings ↔	Multivariate regression	4
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1996 Li C. et al. Taiwan [53]	1340*	Self-Report	-carpets ↔	Comparison of means	3
1997 Yang et al. Taiwan [54]	4164*	Self-report	-carpets ↑	Comparison of means	3
1997 Wickens K. et al New Zealand [52]	474*	self-report	-carpet more than 1 year old ↑	Univariate regression	4
2001 Kipelnäinen et al. Finland [30]	10667*	Self-Report	-carpets ↑	Comparison of means	2
2006 Haverinen-Shaughnessy et al. Finland [22]	363	Inspection	-Renovated plumbing ↑ -pool/sauna ↔	Multivariate regression	5
2013 Sun & Sundell. USA [35]	2819*	Self-report	Vs wallpaper -drywall ↓ OR 0.58 (0.33-0.99) -laminated panel ↔	Pearson X^2 and p values And Multivariate regression	4
2015 Liu et al. China [38]	15 266*	Self-report	Vs latex paint -wallpaper ↓ aOR 0.65 (0.49-0.86) Vs solid wood -Carpet ↔	Multivariate regression	4
2016 Lanthier-Veilleux, Genereux & Baron Canada [34]	2097 Students	Self-report	-carpets ↑ OR 1.54 (1.18-2.00)	Univariate regression	3
2014. Takaoka et al. Japan [48]	1048*	Self-report	-painting last 12 months ↔ -new flooring last 12 months ↑ OR 4.07 (1.99-8.34)	Univariate regression	3
2020 Cai et al. China [29]	8947	Self-report	-redecorated in last year ↑ OR 3.1 (1.8-5.2) 2019 only **Childs's bedroom (2010)**	Multivariate regression	4

			Vs laminate wood -Flooring tile stone or cement ↑ OR 2.70 (2.00, 3.65) -Flooring “other” ↔ Vs latex paint -Walls lime or cement ↑ OR 2.16 (1.68-2.76) -Walls other ↔ **Childs’s bedroom (2019)** -Redecorated in last year ↑ OR 3.52 (1.82-6.83) Vs laminate wood -Flooring tile stone or cement ↔ -Flooring “other” ↔		
CONDENSATION					
2013 Sun & Sundell. USA [35]	2819*	Self-report	vs wooden floor -carpet ↔ -PVC flooring ↑ aOR 1.92 (1.04-3.56) -Wall coverings ↔	Pearson X^2 and p values And Multivariate logistic regression	4
2015 Liu et al. China [38]	15 266*	Self-report	Vs latex paint -wallpaper ↓ aOR 0.49 (0.28-0.85) Carpet ↔	X^2 And Multivariate logistic regression	4
2014. Takaoka et al. Japan [48]	1048*	Self-report	-painting last 12 months ↔ -new flooring last 12 months ↔	Univariate regression	3
2020 Cai et al. China [29]	8947	Self-report	**Childs’s bedroom (2010)** Vs latex paint -Walls lime or cement ↓ OR 0.67 (0.56-0.81) -Walls other ↓ OR 0.78 (0.67-0.92) Vs laminate wood -Flooring tile stone or cement ↓ OR 0.52 (0.45-0.61) -Flooring “other” ↓ OR 0.67 (0.56-0.81) **Childs’s bedroom (2019)** Vs laminate wood -Flooring tile stone or cement ↓ OR 0.57 (0.36-0.89) -Flooring “other” ↓ OR 0.49 (0.31-0.79) -Walls ↔	Multivariate regression	4
MOULDY ODOUR					
2014. Takaoka et al. Japan [48]	1048*	Self-report	-new flooring last 12 months ↔	Univariate regression	3
2020 Cai et al. China [29]	8947	Self-report	-redecorated in last year ↑ aOR 2.8 (1.2-2.4) 2019 only -Walls ↔ -Flooring ↔		4
2022 Sun et al. Canada [42]	199	Self-report	-Carpet ↓ Probability % (Edmonton) 26 (12-49)	Multivariate regression	4

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.5.3 Discussion construction factors

In terms of the external construction characteristics, there were few clear associations with indoor dampness, except that wooden window frames were consistently associated with reduced likelihood of condensation (likely due to less air-tight construction, as pointed out by other authors [43]), and flat roofs are consistently associated with increased likelihood of indoor dampness. Subfloor dampness problems also appear consistently associated with indoor dampness and mould, but these problems do not appear to be driven solely by foundation type, but by other factors leading the foundations to be damp, including poor insulation of concrete slabs [45]. Houses without sun appear to have a higher likelihood of indoor dampness and mould, although the evidence is relatively weak. Future studies on this issue should consider including measurements of window area and orientation, as well as shading on the house from trees hills etc. Another, potentially simpler method would be to measure light intensity (lux) indoors. If lux as well as total window area were measured, alongside window type and glazing (single/double etc), researchers may potentially be able to examine the relationship between heat loss and solar gain, both of which are influenced by window construction.

There is a pattern across several construction characteristics (including house type and size) that have the reverse relationship to condensation than with visible mould or signs of dampness. Ground or top floor vs any other level, PVC or aluminium windows vs wooden are external features showing this pattern, and wall and floor linings are internal features also demonstrating this pattern. Condensation is caused when there is a large enough temperature differential between indoors and out. In other words, condensation can be seen as an indicator of indoor heating, and this may explain why it is often seen in houses with no mould.

Also, several internal linings (flooring bamboo, wallpaper vs latex paint) were associated with less condensation while either not associated or associated with more signs of dampness or mould . This may be reflective of the influence of moisture buffering, where moisture absorbent materials modulate the amount of moisture in the air. More attention should be paid to the influence of indoor surfaces on surface and air humidity.

Finally, redecorating may frequently be an indicator of past water damage, and therefore the associations may reflect reverse causation.. The evidence is currently insufficient to determine whether remediated dampness issues are of ongoing concern, but the evidence here suggests that remediation failed to entirely eliminate the exposure.

2.6 Building Age and Condition

2.6.1 Building age

Building age was the most common house characteristic reported in relation to dampness outcomes, in thirty studies from Northern Europe (7), North America (6), East Asia (5), the UK (5), South-East Asia (2) Central Europe (1), the Mediterranean (1), Oceania (1) and two multi-centred studies (2). Older buildings were found to be associated with higher relative humidity in two of three studies reporting on this outcome [24, 27], with the third, a pilot, reporting on a very small sample of houses (25) finding no association [56].

Four large studies assessed associations with visible mould while adjusting for confounding by other housing characteristics. All four studies found that likelihood of mould increased with building age. The largest of these studies showed a dose-response association of self-reported visible mould with increasing building age, after adjusting for other housing characteristics including house type and heating system (Vs *built since 1980*, aORs for: *1971-1980* 1.38 (1.19-1.60); *1961-1970* 1.60 (1.38-1.86); and *pre-1960* 1.78 (1.56-2.02); Table 2.8) [46]. In the UK, Oreszczyn et al., also found that newer houses had less (inspected) mould compared to those built in 1930 or earlier (*built 1930-1965*; aOR 0.64 (0.49-0.83); *built after 1965* aOR 0.66 (0.46-0.96); Table 2.8). Also in agreement, Cai et al., found less self-reported visible mould in newer houses with a dose-response in both years the survey was conducted (Vs *built before 1991*, aORs for: *2010 survey, after 2000* 0.54 (0.38-0.78); *2019 survey, 1991-2000* 0.31 (0.14-0.69) and *after 2000* 0.21 (0.11-0.41); Table 2.8), although not all the categories were statistically significant (data not shown) [29]. Liu et al., reported on a large sample of mostly newer houses, reporting that compared to houses built before 1980, newer houses had less self-reported visible mould (*Vs built before 1980;* aORs for *1980-1990* 0.65 (0.44-0.95) and *post 2005* 0.43 (0.24-0.77), with intermediate categories non-significant reductions in odds [38].

Other studies also showed increased odds of visible mould in older houses (or its corollary, less mould in new houses), and significant results in at least some age categories in multivariate analysis (adjusting for other house characteristics) [11, 47] and in univariate analysis [24, 41]. In fact, the only study not showing that the newest homes were associated with less mould, had a small sample and did find increased visible mould in older houses, but this was not statistically significant when analyses were adjusted for education (a proxy of SES) and occupant density [57].

A very similar picture is seen when looking at building age in relation to signs of indoor dampness, with, in general, studies reporting more dampness in older houses; in North America [34-36, 58], the UK [59], Northern Europe [6, 22, 32, 40], the Mediterranean [57], East Asia [43, 60] and South-East Asia [54, 61]. However, a few studies reported no association between damp and building age [53, 62], or inconsistent associations [58, 63].

Three studies from East Asia showed a similar pattern, with condensation associated in the opposite direction from other dampness outcomes in relation to building age, despite analyses being adjusted for window type or other characteristics. Sun et al., reported that the newest houses (built after 2000 Vs 1940-1960) were associated with less visible mould (aOR 0.61 (0.44-0.86)) and damp stains (aOR 0.70 (0.52-0.93)) but increased water damage (aOR 1.84 (1.13-3.00)) and condensation (aOR 1.67 (1.23-2.27) Table 2.8) in multivariate analysis adjusting for window type [11]. Similar results were shown in a study from Liu et al, who reported less visible mould (aOR 0.43 (0.24-0.77)), damp stains (aOR 0.62 (0.40-0.96) and water damage (aOR 0.78 (0.68-0.89); Table 2.8), but increased window condensation (aOR 1.64 (1.17-2.31) Table 2.8) in a large sample of newer homes. These analyses were also adjusted for window type and glazing (single/double etc) as well as other house characteristics [38]. A third study, again showed a similar result with the newest (built since 2000) houses associated with reduced odds of visible mould (aOR 0.15 (0.38-0.78) (2010) & aOR 0.21 (0.11-0.41) (2019) Table 2.8), damp stains (aOR 0.31 (0.24-0.41) (significant in 2010 only) Table 2.8), but increased likelihood of condensation (aOR 2.05 (1.64-2.65) (significant 2010 only) Table 2.8) [29]. These analyses were adjusted for other house characteristics including house type, size and ventilation patterns, but not window type. Of note the survey conducted in 2010 was conducted during the cold season when heating was more likely to be used, while the survey conducted in 2019 was not [29].

On the other hand, studies from the Mediterranean [57] and North America [35] reported less condensation in newer buildings rather than more, while in a large multi-centre study from across Europe, a U-shaped association was observed between building age and condensation with houses built between 1945 and 1965 having the greatest likelihood of having reported condensation (data not shown)[28].

2.6.2 Building condition

Three studies reported associations between overall building condition and indoor dampness. A study from the UK used inspected dampness and condition ratings, found that "Poor repairs" were associated with increased signs of dampness or mould indoors [64]. In a study from Oceania, self-reported visible mould was more likely to be present in homes self-rated as average, poor or very poor condition (aOR 1.97 (1.25-3.11) Table 2.8) in multivariate analysis, adjusted for building age (more, or less, than 22 years), and other house characteristics [41]. Furthermore, in univariate analysis this characteristic was associated in a dose-dependent way with visible mould (*Vs Excellent condition*, ORs for *Good* 1.79 (1.34 2.41), *Average* 2.29 (1.44-3.63) and *Poor/very poor* 2.60 (1.38-4.92)). Another study, from North America, again relying on self-reports, also found a dose-response associations of increased signs of indoor dampness with increasingly poor house condition (Vs *regularly maintained*, ORs for *Needs minor maintenance* 3.40 (2.74-4.22) and *Needs major maintenance* 14.78 (9.99-21.88); Table 2.8)[34].

A unique study from Northern Europe assessed a random sample of 450 private houses for moisture related damage – categorised as: wall leaks, roof leaks, plumbing leaks, machinery leaks, and leaks in ventilation ducting. This study showed that flat roofs, associated particularly with homes built in the nineteen seventies, were associated with most moisture damaged [51]. A second study considering external leaks in the roof, from Oceania, reported no association with visible mould, but it did find an association with inspector-assessed indoor dampness and musty odour (Table 2.8)[50].

Another unique study from North America was a randomised trial involving home remediation. All participants in the study received advice on maintaining healthy indoor air quality, and half of the group were also randomly assigned to a home remediation intervention [65]. Remediations were focused on reducing water infiltration with external repairs, removing water damaged materials, installing extract fans in kitchens and bathrooms, changing heaters, repair of stormwater systems and reducing subfloor dampness along with cleaning of existing mould by sanitation experts. The intervention houses had significantly less visible mould 12 months after the intervention was completed [65], although the difference was small.

Table 2.8 Building age and condition

STUDY	Number of houses	Damp Self-report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
1998 Douwes et al. Germany [56]	25	Self-report & inspection	-age of house ↔	Comparison of means	3
2006 Oreszczyn et al. UK [24]	3099	Inspection	Vs pre-1930 -built 1930-1965 OR 0.64 (0.49-0.83) -built after 1965 OR 0.66 (0.46-0.96)	Univariate regression	4
2021 Psomas et al. Sweden [27]	1400	Inspection	-older building ↑	Comparison of means	3
VISIBLE MOULD					
1989 Brunekreef et al 6 U.S cities [58]	4625*	Self-report	-Age (worst 1940-1969) ↑	Comparison of means	2
2002 Zock et al 18 countries [46]	19 218*	Self-report	Vs built since 1980 -built 1971-1980 aOR 1.38 (1.19-1.60) -built 1961-1970 aOR 1.60 (1.38-1.86) -built pre-1960 aOR 1.78 (1.56-2.02)	Multivariate regression	4
2005 Howden-Chapman et al New Zealand [41]	613	Self-report	Vs built since 1983 -older than 22 years ↑ aOR 1.5 (1.01-2.22) vs Good/Excellent -Condition of the house Average/poor/very poor ↑ aOR 1.97 (1.25-3.11)	Multivariate regression	4
2006 Kercsmar et al. Ohio USA [65]	51	Inspection	-remediation ↓	Wilcoxon rank score	3
2006 Oreszczyn et al. UK [24]	3099	Inspection	VS built pre 1930s -built 1930-1965 ↓ aOR 0.64 (0.49-0.83) -built after 1965 ↓ aOR 0.66 (0.46-0.96)	Multivariate regression	5
2009 Sun et al. China [49]	115	Self-report	Vs built 1940-1960 -built 1977-1983 ↔ NS -built1994-1999 ↓ OR 0.24 (0.16-0.38) -built after 2000 ↓ OR 0.61 (0.44-0.85)	Multivariate regression	3
2012 Keall et al New Zealand [50]	891	Inspection	Vs none -minor leaks ↔ -major leaks ↔	Pearson's correlation coefficient	3
2015a Sharpe et al. UK [47]	671	Self-report	-age of house Vs built since 1982 1967-1981 NS 1955-1966 ↑ OR 2.8 (1.5-5.3) Built pre 1954 ↑ OR 2.5 (1.3-4.8)	Multivariate regression	4
2015 Liu et al. China [38]	15 266*	Self-report	vs house built prior to 1980 -1980-1990 ↓ OR 0.65 (0.44-0.95) -1991-2005 NS -2006-2015 ↓	Multivariate regression	4

			OR 0.43 (0.24-0.77)		
2020 Cai et al. China [29]	8947	Self-report	**Childs's bedroom (2010)** vs built 1990 earlier -Built 1991-2000 ↔ -Built after 2000 ↓ AOR 0.54 (0.38-0.78) **Childs's bedroom (2019)** vs built 1990 earlier -Built 1991-2000 ↓ AOR 0.31 (0.14-0.69) -Built after 2000 ↓ AOR 0.21 (0.11-0.41)	Multivariate regression	4
2021 Sousa et al. Portugal [57]	76	Inspection	Vs built before 1950 -Built before 1970 ↔	X^2	3
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1987 Martin CJ et al. Edinburgh [63]	300	Inspection	-built between 1930-1936 ↑	X^2	3
1989 Platt SD et al Edinburgh, London and Glasgow [64]	597	Inspection	-Poor repair ↑	X^2	3
1989 Brunekreef B et al 6 U.S cities [58]	4625*	Self-report	Vs built before 1940 -1940-1969 ↑ -after 1969 ↔	Comparison of means	2
1994 Spengler J. et al USA & Canada [36]	12842*	Self-report	vs built 1970 or after -built before 1970 ↑	Multivariate regression (data not shown)	3
1996 Li C. et al. Taiwan [53]	1340*	Self-report	-age of house ↔	Comparison of means	3
1997 Yang et al. Taiwan [54]	4164*	Self-report	-older than 10 years ↑	Comparison of means	3
1998 Nevalainen et al. Finland [51]	450	Inspection	**Wall leaks** -house built in 1980s ↑ -house built in 1950s ↓ **Roof leaks** -house built in 1970s ↑ -house built in 1980s ↓ **Plumbing leaks** -house built in 1960s ↑ -house built in 1980s ↓ **Machinery leaks** -house built in 1980s ↑ -house built in 1950s ↓ **Leaks in ventilation ducting** -house built in 1980s ↑ -house built in 1950s ↓ **Total moisture damage** -built in 1970s ↑	Comparison of means	3
2000 Holscher et al. UK [59]	2198*	Self-report	-built before 1970 ↑	Corrected contingency coefficient (based on Pearson's X^2	3
1999 Koskinen O et al Finland [40]	310	Inspection	-House >25 years old ↑	comparison of means.	4
2001 Engvall, Norby and Norback. Sweden [62]	3241	public records	-age of house ↔	Not reported	2
2006 Haverinen-Shaughnessy et al. Finland [22]	363	Inspection	-age of house ↑ OR 1.03 (1.02-1.04)	Multivariate regression	5
2006 Gunnbjornsottir et al Iceland, Norway, Sweden, Denmark, Estonia [32]	16190	Self-report	-age of house ↑	Comparison of means	3
2009 Sun et al. China [49]	115	Self-report	**Water damage** Vs built 1940-1960 -built 1977-1983 ↑ aOR 2.80 (1.74-4.54) -built1994-1999 ↓ aOR 0.53 (0.31-0.92) -built after 2000 ↓ aOR 1.84 (1.13-3.00) **Damp Stain** Vs built 1940-1960	Multivariate regression	3

			-built 1977-1983 ↔ -built1994-1999 ↓ OR 0.24 (0.17-0.35) -built after 2000 ↓ aOR 0.70 (0.53-0.93)		
2011 Takoaka & Norback. Japan [60]	153*	Self-report	-older houses ↑	X^2	3
2012 Keall et al New Zealand [50]	891	Inspection	**A little damp** Vs none -minor leaks -major leaks ↔ **Very damp** -major leaks ↔ -major leaks ↑	Pearson's correlation coefficient	3
2013 Sun & Sundell. USA [35]	2819*	Self-report	-built before 1983↑	X^2	4
2014 Choi et al. South Korea [61]	2740*	Self-report	-built since 1993 ↓	X^2	3
2015 Liu et al. China [38]	15 266*	Self-report	-built before 1980↑ vs house built since 1981 1980-2005 NS 2006-2015 ↓ aOR 0.62 (0.40-0.96)	Multivariate regression	4
2016 Lanthier-Veilleux, Genereux & Baron, Canada [34]	2097*	Self-report	Vs pre-1961 -built 1981-2000 ↓ OR 0.65 (0.49-0.87) -built post 2000 ↓ OR 0.27 (0.19-0.39) Vs regularly maintained -Needs minor maintenance ↑ OR 3.40 (2.74-4.22) -Needs major maintenance ↑ OR 14.78 (9.99-21.88)	Univariate regression	3
2016 Thacher et al. Sweden [6]	3798*	Self-report	-built before 1975 ↑ -built after 1975 ↓	X^2	3
2019 Kong et al. China [43]	7865	Self-report	-built before 1993 ↑ aOR 2.6 (1.3-5.2)	Multivariate regression	4
2020 Cai et al. China [29	8947	Self-report	**Childs's bedroom (2010)** vs built 1990 earlier -Built 1991-2000 ↓ aOR 0.3 (0.1-0.7) **Childs's bedroom (2019)** vs built 1990 earlier -Built after 2000 ↓ aOR 0.3 (0.1-0.9)	Multivariate regression	4
2021 Sousa et al. Portugal [57]	76	Inspection	Vs built before 1950 -Built before 1970 ↑	X^2	3
CONDENSATION					
2009 Hagerhed-Engman et al Sweden [31]	8918	Self-Report	-Vs House built pre1960 -built 1960-1983 ↓ OR 0.96 (0.80-1.15) -built post 1983 ↓ OR 0.38 (0.24-0.62)	Multivariate regression for detached houses only	4
2009 Sun et al. China [49]	115	Self-report	Vs built 1940-1960 -built 1977-1983 ↑ aOR 1.93 (1.35, 2.78) -built 1994-1999 ↔ -built after 2000 ↑ aOR 1.67 (1.23, 2.27)	Multivariate regression	3
2013 Sun & Sundell. USA [35]	2819*	Self-report	Vs built 1940-1960 -built 1977-1983 ↔ NS -built1994-1999 ↓ OR 1.22 (0.89, 1.66) -built after 2000 ↓ OR 1.67 (1.23, 2.27)	Multivariate regression	4
2017 Norback et al. Europe [28]	7127 [with	Self-report and inspection	-built 1945-1965 ↑	Multivariate regression	4

	subsample of 3118 inspected				
2015 Liu et al. China [38]	15 266*	Self-report	vs built 1980 later -1980-1990↑ aOR 1.30 (1.01-1.67) -1991-2000 ↑ aOR 1.52 (1.19-2.62) -2001-2005 ↑ aOR 1.91 (1.40-2.62) -2006-2015 ↑ aOR 1.64 (1.17-2.31)	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**(2010)** vs built 1990 earlier -Built 1991-2000 ↔ -Built after 2000 ↑ aOR 2.5 (1.4-4.4) **(2019)** vs built 1990 earlier -Built 1991-2000 ↔ -Built after 2000 ↔	Multivariate regression	4
2021 Sousa et al. Portugal [57]	76	Inspection	Vs built before 1950 -Built before 1970 ↑	X^2	3
MOULDY ODOUR					
2009 Hagerhed-Engman et al Sweden [31]	8918	Self-report	Vs House built pre1960 -built1960-1983 NS -built post 1983 ↓ OR 0.21 (0.08-0.52)	X^2 for all data Multiple regression for single family houses only	3
2012 Keall et al New Zealand [50]	891	Inspection	Vs none -minor leaks ↑ Rho 0.09 -major leaks ↑ Rho 0.10	Pearson's correlation coefficient	3
2015 Sharpe et al. United States [69]	8412*	Self-report	-built before 1990 ↑	Data not shown	1
2015 Liu et al. China [38]	15 266*	Self-report	vs built 1980 later -1980-1990 ↔ -1991-2000 ↓ OR 0.73 (0.55-0.99) -2001-2005 ↓ OR 0.66 (0.45-0.98) -2006-2015 ↔	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**(2010)** vs built 1990 earlier -built 1991-2000 ↓ aOR 0.72 (0.54-0.98) -Built after 2000 ↓ aOR 0.54 (0.41-0.70) -redecorated in last year ↔ **(2019)** vs built 1990 earlier -built 1991-2000 ↔ -built after 2000 ↓ aOR 0.49 (0.27--0.89) -redecorated in last year ↑ aOR 2.8 (1.7-4.7)	Multivariate regression	4
2021 Sousa et al. Portugal [57]	76	Inspection	Vs built before 1950 -Built before 1970 ↔	X^2	3
2022 Sun et al. Canada [42]	199	Self-report	Vs built 1990 or after Adjusted probability (%) -built before 1990 -Edmonton ↑ 84 (60, 90) -Halifax ↑ -Montreal ↔ -Windsor ↔	Multivariate regression	3

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.6.3 Discussion building age and condition

The association of generally increasing dampness and mould with age of the building when using relatively wide building-age intervals, while also observing inconsistent associations with dampness when using smaller build-age increments (e.g. by decade vs 30 - 40-year blocks) may reflects a combination of two factors. Firstly, it likely reflects real degradation over time, where buildings are insufficiently maintained, and this acts as an important driver of indoor dampness and mould. Secondly, construction methods and materials shift over time, and these changes can be likened to fashion, where multiple characteristics (reflecting materials and methods) may group together in time and space. This grouping makes identifying individual characteristics as risk factors for dampness and mould more difficult, even while demonstrating a group at higher risk overall [31, 63, 64].

The previous sections have highlighted the likelihood of indoor dampness associated with damp basements and subfloors (and uninsulated concrete slabs)(see section 2 'Construction factors'), and Brunekreef et al., report that prevalence of damp basements increases with age of the house [58].This suggests that moisture intrusion into subfloors and basements increases over time, and so these spaces need to be considered as an important aspect of house maintenance.

Several studies have identified a U-shaped dose-response association in terms of house age and repair, with the oldest and newest houses in better repair than houses of medium age [22, 41]. This may be due to buildings over a certain age gaining heritage value, and hence becoming owned by wealthier owners, who are more able to undertake requisite repairs. Only one study included both characteristics (age and condition) in mutually adjusted analysis (further adjusted for other characteristics), which reported that both older houses (>22 years) and those in poor repair remained significantly associated with increased likelihood of indoor visible mould, with poor repair a slightly stronger and more statistically significant result. So, there may be other characteristics associated with older houses as well as poorer condition, that make them more susceptible to indoor dampness. Lanthier-Veilleux showed poor maintenance was a strong predictor of increased indoor dampness, monthly rental cost was not associated with indoor dampness, while the landlord proximity was strongly associated with significantly reduced indoor dampness and mould, pointing towards the ease and likelihood of repair being a primary driver of dampness risk [34].

In summary, studies assessing the condition of the house or building are consistent in showing an association between poor condition and indoor dampness and mould, while age of the building was generally, but less consistently, associated with worse indoor dampness outcomes. Obviously, the age is likely related to building condition, and it is likely that much of the association between older buildings and indoor dampness and mould can be explained by poor repair, which can be described as degradation over time combined with a lack of maintenance. All buildings need to be maintained, but some also have higher risk from the outset due to methods and materials used that have a higher risk of failure. Some poor construction methods and materials can be improved as part of ongoing maintenance of the building. For example, in New Zealand, window flashing standards have been improved. This is well understood by builders, and most houses, if they having repairs done on the home, will have these flashings replaced and upgraded to the newer standard, for relatively low cost. Risk methods that are design features, such as internal gutters, flat roofs and sheet wall claddings are harder to improve, and therefore need even more attention to maintenance.

2.7 Tenure and socioeconomic status

2.7.1 Tenure

A number of studies were restricted by tenure, some reporting only on owner-occupied [42, 66] and others only rental houses [24, 47, 65]. Some studies adjusted analyses for socioeconomic status [35], or education level but did not report associations.

Three studies reported on the association between tenure-type and visible mould with all three reporting no association, from East Asia [29, 38] and the UK [64]. Both studies from East Asia, while finding no association between tenure type and visible mould, found that rental places were more likely to have other dampness outcomes. Cai et al., found an association with mouldy odour (aORs for: *2010* 1.50 (1.23-1.81), *2019* 1.52 (1.14-2.03) Table 2.9) and water damage (2019 only aOR 1.38 (1.00-1.91) Table 2.9) [29] and the study by Liu et al., observed less mouldy odour in owner occupied (vs rental) houses (aOR 0.78 (0.67-0.91) Table 2.9) but this study found no association with water damage or condensation [38].

In all, seven studies reported on the association between tenure types and signs of indoor dampness from the UK (1), Northern Europe (2), North America (1), and East Asia (2), and South-East Asia (1). Three reported that rental homes had a higher likelihood of dampness compared to owner-occupied homes (Table 2.9), from Northern Europe [31], the UK [67], and North America [34], and three reported no association, from Northern Europe [68], South-East Asia [53], and East Asia [38]. One study from

East Asia, which conducted the same survey twice, in 2010 and 2019, reported no association in 2010, the year the survey had been conducted in winter and spring, while unadjusted analyses showed a statistically significant increased likelihood in 2019, when it was conducted during summer (*vs owner-occupied; Tenant* aOR 1.38 (1.00-1.91); Table 2.9) [29].

Two studies from East Asia reported on the relationship between tenure and condensation; one reported no relationship [38], and the other (which was not adjusted for other factors) reported less condensation for rental properties in 2010, whilst no association was observed in 2019 [29] (Table 2.9). This was the reverse to what was observed for signs of dampness i.e. in 2010 (spring and winter), rentals were not associated with dampness whilst in 2019 (summer) rentals had more dampness. These results could be explained by differential temperature (as discussed earlier), as in cold seasons increased temperature indoors (as a result of heating) increases the risk for condensation. Indoor temperature is often a function of airtightness as well, and so reduced condensation could be explained here by tenants living in draughtier houses which are colder in winter. This finding that rental houses may be more damp overall is consistent with findings from the same study showing that mouldy odour was more prevalent in rental houses (2010 aOR 1.5 (1.23-1.81), and 2019 aOR 1.70 (1.18-2.44); Table 2.9) [29].

Two other studies reported associations between tenure and mouldy odour, from East Asia and North America, both reporting the same direction of effect, with rentals at increased likelihood of mouldy odour (vs tenant ; owner-occupied aOR 0.78 (0.67-0.91) Table 2.9) [38], and (rental home OR 1.36 (1.73-3.13) Table 2.9) [69]. Mouldy odour was the only dampness outcome for which the results were consistent across studies for tenure status and dampness outcomes. With tenants consistently found to be living in homes with more mouldy or musty odour.

2.7.2 Socioeconomic status

One study, from the UK, in a large sample of lower socioeconomic rental homes, reported SES in relation to moisture measurements (RH). This study found that while there was no difference by deprivation index category (based on area), those participants who answered yes to the question “Do you have any difficulty paying bills?” had on average 2.3% higher RH in living rooms and 2.8% higher RH in bedrooms than those who did not struggle with their bills (data not shown in tables)[24].

The same study also looked at the association between SES and visible mould, and found a fairly consistent relationship with higher deprivation index and increased likelihood of inspector-assessed mould (*vs least deprived (quartile 1); quartile 2*, OR 1.79 (1.26-2.56); *quartile 3*, OR 1.65 (1.13-2.41) and *quartile 4,* OR 1.68 (1.11-2.55); Table 2.9) in univariate regression analysis [24]. Another study, also from the UK, and also in a sample of lower socioeconomic rental households, did not find an association between deprivation level and self-reported visible mould (Table 2.9) when adjusting for some other house characteristics [47].

A large multi-centre study from throughout Europe, which assessed SES in terms of occupation (manager or professional/technical/other work – not manual/manual work), as well as by education level (>20 years/17-20/≤16), found self-reported visible mould was reported more frequently by those on the bottom end of both these scales (*vs manager or professional; manual worker* aOR 1.27 (1.03-1.55) and *vs > 20 years* *education; ≤ 16 years* aOR 1.25 (1.03-1.52) Table 2.9). However, these associations were not borne out when compared with a subsample (n=3118) with inspector-assessed visible mould, in multivariate analysis, adjusted for building age and climatic factors [28]. The authors suggested that the discrepancy may be ascribed to differences in the assessment, with self-reported mould being asked in relation to the last twelve months, while the inspector assessed mould was related only to mould visible on the day of inspection [28]. This conclusion is somewhat borne out by the contiguous finding that manual workers were more likely to live in houses with damp spots – identified by inspectors – although when considering number of years of education, was unassociated (vs manager or professional; manual work aOR1.55 (1.17-1.61) Table 2.9), since mould may be easier to clean off than damp spots. Finally, in relation to visible mould, a small study (n=76) from the Mediterranean found no relationship between years of education and inspected visible mould (Table 2.9) [57].

Continuing with results from the large multi-centre study discussed above, self-reported water damage was found to occur significantly less in the homes of manual workers and those with fewer years of education (vs manager or professional; manual work aOR 0.69 (0.53-0.89), *vs > 20 years education; ≤ 16 years* aOR 0.77 (0.60-0.98), although, as discussed, inspectors also found more damp spots in this group of homes (Table 2.9) [28]. Conversely, self-reported damp spots were not associated with SES indicators in the same analysis (Table 2.9).

Only two studies reported on the relationship between SES and condensation, with the same large multi-centre study reporting more condensation with indicators of lower SES (*vs manager or professional; other work, not manual* aOR 1.45 (1.17-1.81), *manual work* aOR 1.50 (1.19-1.90) and *vs > 20 years education; ≤ 16 years* aOR 1.80 (1.44-2.27)

Table 2.9) [28]. The smaller study from the Mediterranean reported similar results (less condensation with more years of education (Table 2.9)[57].

Finally, just one study, from North America, reported on the association between indicators of SES and mouldy odour. This study found that lower SES was associated with more indoor mouldy odour (living in poverty OR 1.58 (1.19-2.09); Table 2.9) [69].

Table 2.9. Tenure and socio-economic status

STUDY	Number of houses	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
2006 Oreszczyn et al. UK [24]	3099	Inspection	-deprivation level ↔ Vs no difficulty -difficulty paying bills ↑	X^2	4
VISIBLE MOULD					
1989 Platt SD et al. Edinburgh, London and Glasgow [64]	597	Inspection	-Type of building ↔ (council vs private landlord)	X^2	3
2006 Oreszczyn et al. UK [24]	3099	Inspection	vs quartile 1 (least deprived) -deprivation quartile 2 ↑ OR 1.79 (1.26-2.56) -deprivation quartile 3 ↑ OR 1.65 (1.13-2.41) -deprivation quartile 4 ↑ vs no difficulty -difficulty paying bills ↑ OR 2.20 (1.55-2.70)	Multivariate regression (adjusted for year and area only)	5
2015 Liu et al. China [38]	15 266*	Self-report	vs tenant -owner occupied ↔	Multivariate regression	4
2015a Sharpe et al. UK [47]	671	Self-report and public records	vs least deprived (IMD 9-21) -IMD ≥21-26 ↔ -IMD ≥26-60 ↔	Multivariate regression	4
2017 Norback et al. Europe [28]	7127 [with subsample of 3118 inspected	Self-report and inspection	**Self-reported mould** vs manager/professional -Technical ↔ -Other work not manual ↔ -manual work ↑ aOR 1.27 (1.03-1.55) vs > 20 years education -17-20 years ↔ -≤ 16 years ↑ aOR 1.25 (1.03-1.52) **Inspected mould** vs manager/professional -Technical ↔ -Other work not manual ↔ -manual work ↔ vs > 20 years education -17-20 years ↔ -≤ 16 years ↔	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	-Tenant ↔	Multivariate regression	4
2021 Sousa et al. Portugal [57]	76	Inspection	-years of education ↔	X^2	3
VISIBLE DAMPNESS & MOULD/WATER					

DAMAGE/FLOOR MOISTURE					
1994 Packer et al. UK [67]	2353	Self-report	Rented ↑	Comparison of means	3
1994 Spengler J. et al USA & Canada [36]	12842*	Self-report	-years of education ↑ -higher income ↑	Multivariate regression (data not shown)	3
1996 Pirhonen I. et al. Finland [68]	1460*	Self-report	-years education ↑(NS) -occupation ↔ -tenant ↔	Comparison of means	3
1996 Li C. et al. Taiwan [53]	1340*	Self-report	vs tenant -owner occupied ↔	Comparison of means	3
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	vs owner -tenant ↑ OR 5.47 (3.03-9.87)	Multivariate regression for single family houses only	4
2015 Liu et al. China [38]	15 266*	Self-report	vs tenant -owner occupied ↔	Multivariate regression	4
2016 Lanthier-Veilleux, Genereux & Baron. Canada [34]	2097 Students	Self-report	vs tenant -owner occupied ↓ OR 0.50 (0.40-0.63)	Univariate regression	3
2017 Norback et al. Europe [28]	7127 [with subsample of 3118 inspected	Self-report and inspection	**Self-reported water damage** vs manager/professional -Technical ↔ -Other work not manual ↔ -manual work ↓ OR 0.69 (0.53-0.89) vs > 20 years education -17-20 years ↓ NS -≤ 16 years ↓ OR 0.77 (0.60-0.98) **Self-reported damp spots** vs manager/professional -Technical ↔ -Other work not manual ↔ -manual work ↔ vs > 20 years education -17-20 years ↔ -≤ 16 years ↔ **Inspected damp spots** vs manager/professional -Technical ↔ -Other work not manual ↔ -manual work ↑ OR 1.55 (1.17-1.61) vs > 20 years education -17-20 years ↔ -≤ 16 years ↔	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**(2010)** -Tenant ↔ **(2019)** -Tenant ↑ aOR 1.38 (1.00-1.91)	Multivariate regression	4
2021 Sousa et al. Portugal [57]	76	Inspection	-more years of education ↔	X^2	3
CONDENSATION					
2015 Liu et al. China [38]	15 266*	Self-report	vs tenant -owner occupied ↔	Multivariate regression	4
2017 Norback et al. Europe [28]	7127 [with subsample of 3118 inspected	Self-report and inspection	**Inspected** vs manager/professional -Technical ↔ -Other work not manual ↑ aOR 1.45 (1.17-1.81) -manual work ↑ aOR 1.50 (1.19-1.90) vs > 20 years education -17-20 years ↔ -≤ 16 years ↑ aOR 1.80 (1.44-2.27)	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**(2010)** -Tenant ↓	Univariate regression	4

			OR 0.69 (0.60.79) **(2019)** -Tenant ↔		
2021 Sousa et al. Portugal [57]	76	Inspection	-more years of education ↓	X^2	3
MOULDY ODOUR					
2015 Liu et al. China [38]	15 266*	Self-report	vs tenant -owner occupied ↓ OR 0.78 (0.67-0.91)	Multivariate regression	4
2015b Sharpe et al. United States [69]	8412*	Self-report	-Rental home ↑ OR 1.36 (1.73-3.13) -living in poverty ↑ OR 1.58 (1.19-2.09)	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**(2010)** -Tenant ↑ OR 1.50 (1.23-1.81) **(2010)** -Tenant ↑ OR 1.52 (1.14-2.03) -Tenant ↑ aOR 1.70 (1.18-2.44)	Univariate regression	4
2021 Sousa et al. Portugal [57]	76	Inspection	-more years of education ↔	X^2	3

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.7.3 Discussion: Tenure and socioeconomic status

Two studies demonstrated that tenants and those with lower SES lived in homes with more signs of inspected dampness and condensation [28], and more signs of self-reported dampness and mouldy odour [29], both in multivariate analysis adjusted for other house characteristics while also finding no association for the same characteristic with visible mould. On the other hand, in a large multi-centre study, Norback et al., reported differing outcomes for these same groups when comparing self-reported visible mould over the last 12 months, to inspector assessed mould (present on a single day of the inspection). These results point to important behavioural impacts which influence the identification of the exposure, namely cleaning. Surveys assessing exposure to visible mould rarely ask about the frequency of the appearance of mould, or the frequency of needing to clean mould. It is the authors contention, that adding a frequency dimension to exposure assessment surveys may help to improve the accuracy of such assessments, and that this missing (residual) confounding factor may explain why the results here are not more consistent.

As discussed previously (see ‘house type’), relationships between SES and tenure have sometimes been confounded by house type. Kong et al., demonstrated that occupants of detached houses in East Asia were more likely to have lower income and lower education levels compared to apartment dwellers [43], while in Europe, it was demonstrated that higher SES was associated with living in a house rather than an apartment [70], and another study showed 80% of apartments were rentals compared to less than 10% of detached houses [31]. This review suggests that house type is a less important contributor to indoor dampness and mould, than SES and tenant status, which appear more consistently related.

Tenants have little capacity to make repairs or modifications on their homes, as do people on low incomes in owner-occupied homes. The same groups are also less likely to be able to heat their homes sufficiently to maintain a healthy indoor environment, and houses may also be more crowded (see section 2.8). To better understand the relationship between SES, tenure and indoor dampness and mould, studies should aim to collect data (and mutually adjust for these variables in statistical analyses) on each of these confounding characteristics (frequency of cleaning (for mould), house size, number of occupants, indoor winter temperature (or willingness/capacity to heat) and house condition (poor repair)).

Of concern is the finding that mouldy odour is consistently associated with both rental status lower income, since this exposure is the most strongly associated with adverse health effects [7, 62, 71, 72].

2.8 Occupancy

Occupant density is a function of both the number of occupants and the volume of occupied space. Because there is a wide variety in the measures used in assessment of this characteristic, the results by occupancy measure are discussed first, before looking at the associations by dampness outcome. Several assessed number of persons per residence [24, 30, 41], two calculated persons per total rooms in the home [73] or persons and total rooms [39], and others used a ratio of persons per bedroom [41, 47, 74], number of children in the home [52, 63], and some reported on whether the residence was considered overcrowded [47, 63, 64]. Only two small studies calculated persons per cubic metre of interior volume (occupant density) [16, 57].

Of the two studies that used a volumetric occupant density assessment, from North America, and the Mediterranean, one found higher RH in homes with greater occupant density [16], while a study from the Mediterranean, found that inspector-assessed visible mould was slightly less likely in homes with greater occupant density, with the latter analyses adjusted for building age and occupant education (SES), [57]. Both of these studies were based on small (under 100 houses) samples, so results should be interpreted with caution.

Two studies showed dose-response increases in dampness outcomes with each additional person in the house (with one person households as the reference category). In a study from the UK, Oreszczyn et al., demonstrated this pattern (%RH; *vs 1 person*, *2 people* increased RH by an average of 0.63%, the increase *for 3 people* was 2.19%, and *4 or more people* 4.29% per household) Table 10)[24], using mean standardised RH (adjusted for outdoor climate). Additionally, this same study also reported a dose-response association with inspector-assessed visible mould (*vs 1 person* OR for *2 people*

1.69 (1.16-2.46), *2 people* 1.89 (1.20-2.98), and *3 people* 3.01 (2.06-4.40); Table 2.10), with analyses adjusted for year and geographical area [24]. The second study, from Oceania, showed a dose response with per person increases in occupants per residence and self-reported visible mould (*vs 1 person*; aORs for *2 people* 3.29 (1.73-6.26), *3 people* 2.77 (1.35-5.63), *4 people* 4.44 (2.11-9.32), *5 people* 8.15 (3.50-18.95), *6 people* 5.49 (2.00-15.12) and *7 people* 7.05 (1.22-40.82); Table 2.10) in multivariate analysis, adjusting for other house characteristics including building age and (self-reported) condition [41].

Three other studies, also using persons per residence, from Northern Europe (2) and Africa (1), reported that more people per residence was associated with increases in mean RH [27, 39], and proportion of homes with dampness (higher in homes with five or more occupants only) [30] in unadjusted analyses.

Two studies looked at persons per room in the house, from Africa and North America. In the study from Africa, more occupants per house was associated with increased RH, while more rooms per house was associated with lower RH [39]. The study from North America reported that more than 1 person per room in the house was associated with increased odds of inspector-assessed visible mould (OR 1.9 ($p<0.05$)) and increased odds of visible water damage (OR 2.5 ($p<0.05$), Table 2.10) [73].

Two studies from the UK assessed dampness in relation to persons per bedroom. The first study reported higher adjusted RH in the bedrooms with more than one child, (measured in the child's bedroom using a wood block, and adjusted for outdoor conditions over the 7-day measurement period)[74]. In the other study, the same metric (1 only vs more than one child per bedroom) was associated with an increased likelihood of self-reported visible mould anywhere in the house (aOR 3.4 (1.9-5.8), Table 2.10) in multivariate regression analysis, adjusted for month, SES and some housing characteristics)[47].

Three studies reported on dampness in relation to the number of children in the house, from the UK and Oceania. Both studies from the UK reported no difference in the number of children in damp vs dry houses [63, 64]. The study from Oceania reported that more than 3 children in a house was associated with increased signs of dampness in the whole house [52].

Three studies, all from the UK, reported dampness in relation to overcrowding metrics. The first of these reported a non-significant increased likelihood of houses with inspector-assessed signs of dampness being considered as overcrowded (not defined) [63]. The second study, (which was from the same study group and used many of the same protocols as the first) showed no association between overcrowding and inspector-rated indoor mould or dampness. The third study, which considered a house overcrowded with more than two occupants, found that overcrowding was associated with self-reported visible mould in univariate analysis (OR1.6 (0.9-2.5); Table 2.10), although statistical significance was lost when analyses were adjusted for month and other house characteristics including deprivation score [47]. All three of these studies targeted low-income populations, which may have influenced the association with dampness and mould.

Two studies looked at mouldy odour, from North America and the Mediterranean. In the study from four cities in Canada, neither house size (see table 2.5) or number of residents were associated with mouldy odour after testing in univariate and multivariate analysis (Table 2.10)[42]. The other study, from the Mediterranean, found that high (vs low) occupant density was associated with less mould odour, although as noted earlier, this study was based on a small sample [57].

Table 2.10. Dampness by occupancy rate

STUDY	NUMBER	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
1989 Strachan D and Saunders C Edinburg, Scotland [74]	330	Inspection	-shared bedroom ↑	Comparison of means and Multivariate regression	4
1998 Lawton et al. Canada [16]	59	Inspection	-higher occupancy ↑	Correlation coefficient	3
2006 Oreszczyn et al. UK [24]	3099	Inspection	-higher occupancy ↑ Vs 1 occupant -2 persons ↑ +0.65% -3 persons ↑ + 2.19% -4 persons ↑ + 4.29%	Standardised RH regression (adjusted for external conditions)	5
2016 Fakunle et al. Nigeria [39]	132	Inspection	-higher occupancy ↑ -more rooms occupied ↓	Spearman's rank correlations	3
2021 Psomas et al. Sweden [27]	1400	Inspection	-higher occupancy ↑	Comparison of means	3
VISIBLE MOULD					
1989 Platt SD et al Edinburgh, London and Glasgow [64]	597	Inspection	-Overcrowding ↔ -Number of children ↔	X^2	3
2005 Howden-Chapman P et al New Zealand [41]	613	Self-report	**Univariate** Vs <1 occupant (per bedroom) -1-2 persons ↑ NS - ≥3 persons ↑ OR 1.65 (1.26-2.17) **Multivariate** Vs 1 occupant (per house) -2 persons ↑ aOR 3.29 (1.73-6.26) -3 persons ↑ aOR 2.77 (1.37-5.63) -4 persons ↑ aOR 4.44 (2.11-9.32) -5 persons ↑ aOR 8.15 (3.50-18.95) -6 persons ↑ aOR 5.49 (2.00-15.12) 7 persons ↑ aOR 7.05 (1.22-40.82) -8 persons NS	Univariate and Multivariate regression	4/5
2005 Bradman et al. USA [73]	644	Inspection	Vs < 1 person per room -≥1.5 person/room↑ OR 1.9 p≤0.05	Multivariate regression	5
2006 Oreszczyn et al. UK [24]	3099	Inspection	Vs 1 occupant -2 persons ↑ OR 1.69 (1.16-2.46) -3 persons ↑ OR 1.89 (1.20-2.98) -4+ persons ↑ OR 3.01 (2.06-4.40)	Univariate regression	4
2015 Sharpe et al. UK [47]	671	Self-report	**Univariate** -overcrowding ↑ OR 1.6 (0.9-2.6)	Multivariate regression	4

			Multivariate -more than one person per bedroom ↑ aOR 3.4 (1.9-5.80)		
2021 Sousa et al. Portugal [57]	76	Inspection	Vs low occupant density -high occupant density ↑	X^2	3
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1987 Martin CJ et al Scotland [63]	300	Inspection	-Overcrowding ↑ -Number of children ↔	X^2	3
1997 Wickens K. et al New Zealand [52]	474*	Inspection and Self-report	-More than 3 children ↑	Comparison of means	4
2001 Kipelnäinen et al. Finland [30]	10 667*	Self-report	-higher occupancy ↑	Comparison of means	2
2005 Bradman et al. USA [73]	644	Inspection	Vs low occupant density -high occupant density ↑ OR 2.5 p≤0.05	Univariate regression	4
2021 Sousa et al. Portugal [57]	76	Inspection	Vs low occupant density -high occupant density ↑ NS	X^2	3
CONDENSATION					
2021 Sousa et al. Portugal [57]	76	Inspection	Vs low occupant density -high occupant density ↓	X^2	3
MOULDY ODOUR					
2021 Sousa et al. Portugal [57]	76	Inspection	Vs low occupant density -high occupant density ↓	X^2	3
2022 Sun et al. Canada [42]	199	Self-report	-number of occupants ↔	Multivariate regression	4

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.8.1 Discussion, Occupancy

A strong and consistent relationship between occupancy and measures of indoor dampness was shown by studies that defined occupancy as the number of occupants per dwelling. Two of these studies adjusted for other house characteristics, and showed dose-response associations between each increase in one person and the presence of in damp/mould. While one of these studies, from the UK, was in a population with a restricted demographic [24], the other, from Oceania, was a national survey, [41], so results are likely generalisable. Other studies using this measure of occupancy also found positive associations with dampness assessments, and measured moisture [27, 30, 39]. Although none of these studies adjusted for house size, the associations are strong enough that this measure appears robust. The number of children per house was not consistently associated with dampness outcomes, however, the two UK studies using this assessment were drawn from quite homogenous samples, which may have impacted the results. Regardless, overall number of persons is a preferred measure, and not taking into account the number of other household members may have resulted in biased results. Similarly, overcrowding assessments were not consistently associated, and again may have been influenced by non-random samples. As noted above, number of persons per house is a more preferable measure, especially considering that overcrowding metrics can easily be calculated from a simple count during analysis if information on floor area and/or number of bedrooms are also collected.

2.9 Moisture modifiers

2.9.1.1 Gas heating

The use of gas for heating was reported in relation to indoor dampness in eight studies, from Oceania (3), the UK (3), and North America (2). The studies were mostly published before 2000, with many focussing specifically on heaters without a flue (to extract both noxious fumes and moisture produced due to gas combustion). As there is no apparent difference in the results between flued and Unflued gas (UFG) heaters (Table 2.11), this review will not differentiate between them in the following discussion. All but two of these studies reported no association with visible mould [41, 64] or with signs of dampness [36, 50, 63] (Table 2.11). Only the study by Spengler et al., from North America, found higher rates of self-reported dampness and mould in homes using unflued (unvented) gas heaters, as well as slightly higher rates in homes using gas as fuel for cooking [36] (Table 2.11). A small study of 26 homes in New Zealand reported lower RH in living and bedrooms after unflued gas heaters were replaced with heat pumps [75]. Sharpe et al., reported a non-significant reduction in self-reported visible mould for houses using gas heating [47].

2.9.1.2 Gas cooking

The use of gas for cooking was assessed in five studies. All studies were published before 1990, and again, only one found a relationship with dampness. This study, from the UK, showed a positive association between gas cooking and self-reported signs of dampness in unadjusted analyses [59] (Table 2.11).

2.9.1.3 Humidifiers

Humidifiers were assessed in relation with indoor dampness and mould in six studies from Northern Europe (2), North America (2), East Asia (1) and South-East Asia (1).

One large study from East Asia reported no association between the use of humidifiers and self-reported visible mould or mouldy odour using multivariate regression, adjusted for multiple other house characteristics and behaviours. However an association with increased window condensation was found (aOR 1.20 (1.04-1.40), Table 2.11)[38].

A large study from North America reported that humidifier use was positively associated with self-reported signs of dampness and mould [36] (Table 2.11). Another study, from Northern Europe, reported that indoor moisture damage, as assessed by an inspector, was associated with a lower likelihood of humidifier use [22](Table 2.11), while a second study from Northern Europe found that humidifiers were not associated with inspector-assessed signs of dampness. A fourth study, from North America, found that humidifier-use was not associated with indoor self-reported dampness or mould (Table 2.11)[34].

2.9.1.4 Dehumidifiers

Dehumidifiers were assessed for associations with indoor dampness outcomes in five studies, from North America (3) and South-East Asia (2). All five studies reported increases associated with dehumidifier use, in self-reported outcomes of visible mould [58], signs of indoor dampness [21, 53], with one study reporting an odds ratio of OR 2.18 (1.73-2.74; Table 2.11)[34].

2.9.1.5 Plants

Keeping of plants indoors was assessed in association with indoor dampness in two studies, both from South-East Asia. Both reported no association between keeping of indoor plants and self-reported signs of dampness (Table 2.11)[53, 54].

Table 2.11. Use of gas for heating or cooking humidifiers and dehumidifiers & plants (humidity modifying characteristics)

STUDY	NUMBER	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
2015 Boulic et al. New Zealand [77]	26	Inspection	Vs unflued gas heater Heat pump ↓	Comparison of means	3
VISIBLE MOULD					
1989 Platt SD et al Edinburgh, London and Glasgow [64]	597	Inspection	-UFG heater ↔	X^2 with t test for significance	3
1989 Brunekreef B et al. 6 U.S cities [58]	4625*	Self-report	-dehumidifier ↑ -humidifier ↔	Comparison of means	2
2005 Howden-Chapman P et al New Zealand [41]	613	Self-report	-UFG heater ↔ Vs no heating -gas only heating ↔	Univariate regression	4
2015 Liu et al. China [38]	15 266*	Self-report	-humidifier ↔	Multivariate regression	4
2015a Sharpe et al. UK [47]	671	Self-report	-gas heating ↓ NS	Multivariate regression	2
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1987 Martin CJ et al. Edinburgh [63]	300	Inspection	-UFG heater ↔	X^2 & Mann-Whitney U	3
1991 Dales RE. Canada [21]	14799*	Self-report	-UFG heater ↔ -Gas cooking ↔ -dehumidifier ↑	Comparison of means	2
1994 Spengler J. et al. USA and Canada [36]	12842*	Self-report	-Unvented heaters ↑ -gas cooking ↔ -humidifiers ↑	Multivariate regression analysis (data not shown)	3
1996 Li C. et al. Taiwan [53]	1340*	Self-report	-gas cooking ↔ -dehumidifier ↑ -plants ↔	Comparison of means	3
1997 Yang et al. Taiwan [54]	4164*	Self-report	-gas cooking ↔ -plants ↔	Comparison of means	3
1999 Holscher et al. UK [59]	2198*	Self-report	-gas cooking ↑	X^2	3
1999 Koskinen O et al Finland [40]	310	Inspection	-humidifier ↔	comparison of means.	4
2006 Haverinen-Shaughnessy et al. Finland [22]	363	Inspection	-Humidifier ↓	Comparison of means	4
2012 Keall et al. New Zealand [50]	891	Inspection	-UFG heater ↔	correlation coefficient	4
2015 Liu et al. China [38]	15 266*	Self-report	-humidifier ↔	Multivariate regression	4
2016 Lanthier-Veilleux, Genereux & Baron, Canada [34]	2097*	Self-report	-dehumidifier ↑ OR 2.18 (1.73-2.74) -humidifier ↔	Univariate regression	3
CONDENSATION					
2015 Liu et al. China [38]	15 266*	Self-report	-humidifier ↑ aOR 1.20 (1.04-1.40)	Multivariate regression	4
MOULDY ODOUR					
2015 Liu et al. China [38]	15 266*	Self-report	-humidifier ↔	Multivariate regression	4

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.9.2 Discussion: Moisture modifiers

It is notable that none of these parameters were consistently associated with measures of indoor dampness, except for dehumidifier use. It is very likely that the association with dehumidifiers is due to reverse-causation (ie, those with damp houses are more likely to use a dehumidifier). Expected associations, due to the known production of moisture in the combustion of gas for heating and cooking, failed to materialise in numerous earlier studies, and the results were so consistently absent, that few studies since 2000 have included this parameter in their data collection protocols.

Only one of the studies adjusted for ventilation parameters (presence of a bathroom exhaust fan), so it is possible, but unlikely, that ventilation behaviour is obscuring a real association. While this review cannot be considered to clearly demonstrate the association of every house characteristic with indoor dampness, the lack of associations in this particular group of characteristics is surprising, and therefore begs the question of whether moisture in the air is as important as we have been assuming in relation to mould, and even perceived dampness. From the results described in this section, it would appear that moisture producing appliances included here are not important drivers of house dampness.

2.10 Heating and temperature

In total, twenty-eight studies reported associations between temperature or heating characteristics, from North America (6), the UK (9), Northern Europe (5), Oceania (3), East Asia (2), the Mediterranean (1), Africa (1), and one multi-centre study (1).

2.10.1.1 Temperature

Seven studies reported associations between indoor temperature and dampness assessments, from Northern Europe (2), the UK (3), North America (1), and Africa (1). Three studies looked at the association of indoor temperature measurements with indoor Relative Humidity (RH). Of these, two (from Northern Europe) found that higher temperature was associated with reduced RH (Table 2.12)[27, 45], and one (from Africa) reporting the opposite i.e., higher temperature was associated with higher RH (Table 2.12) [39]. Two studies reported associations between temperature measurements and visible mould, from the UK and North America. Both reported that higher temperature was associated with reduced evidence of inspector-assessed visible mould (Table 2.12)[74, 76]. Two studies, both from the UK, reported associations between self-reported coldness indoors and inspector-assessed [64], and self-reported signs of dampness indoors [77], with both reporting that self-assessed cold indoors increased the likelihood of dampness (Table 2.12). One study reported associations between indoor temperature measurements and self-reported condensation. This study found a reduction in condensation with higher temperature (Table 2.12)[74]. Finally, one study from Northern Europe looked at the association between indoor temperature and mouldy odour. This study found that higher temperatures were associated with reduced likelihood of mouldy odour, in a multivariate analysis, adjusted for outdoor temperature (aOR 0.86 (0.75-0.99), Table 2.12)[45].

2.10.1.2 Heating satisfaction

Two studies, both from the UK, assessed satisfaction with the heating system, in association with both RH and with visible mould. One study found that homes where occupants were dissatisfied with the heating system were associated with higher standardised (adjusted for outdoor conditions) RH, and higher likelihood of inspector-assessed visible mould in multiple regression analysis, adjusted for year and geographical area only (aOR 2.05 (1.55-2.70), Table 2.12)[24]. The second study reported that houses where the occupants reported the heating was “inadequate” had three times higher likelihood of self-reported visible mould (OR 3.4 (2.0-5.8))[47].

2.10.1.3 Heating behaviours

Another study, also from the UK, reported on the relationship between bedroom heating behaviours and bedroom RH, finding that both not heating the bedroom and heating it only overnight, were associated with increased (standardised) RH, while heating during the day only and heating both day and night were associated with reduced standardised RH (Table 2.12)[74]. A third study from the UK asked participants whether they chose not to heat due to cost, and those households who said yes (when compared to those who said no) were more likely to live in a house with self-reported visible mould (aOR 2.2 (1.5-3.2), Table 2.12); analyses were adjusted for some house and household characteristics including employment status and presence of insulation [47]

2.10.1.4 Heating type or system

Nineteen studies assessed dampness in relation to heating type from North America (4), the UK (4), Northern Europe (3), Oceania (4), East Asia (2), the Mediterranean (1) and one Multi-centre study (1). The use of gas heaters has been discussed previously in relation to moisture modifying appliances, but we will discuss it again here for comparison with other heater types. Eleven (of eighteen) studies reported that various measures of dampness were not associated with heater type, including four with self-reported visible mould from North America [58], Oceania [41, 50]. One study from Oceania reported lower RH after unflued gas heaters were replaced with heatpumps [78]. On the other hand, one study from the UK reported a lower likelihood of self-reported visible mould, associated with gas heating in univariate analysis, which lost significance when adjusted for other house characteristics, including insulation and the presence of double glazing (OR 0.7 (0.5-1.1), Table 2.12) [47]. Nine studies found no relationship between heater type and signs of dampness, from the UK [20, 63, 64], Northern Europe [31], Oceania [50, 52], North America [21, 34, 58], and Northern Europe (the latter study also found no relationship between heater type and condensation and mouldy odour; Table 2.12)[31].

Two studied reported associations between measured moisture in indoor air (RH) and the presence or absence of central heating (regardless of other heaters), from Oceania, and the Mediterranean. Both reported that average RH was lower in homes with central heating (Average RH = 61% without and 56% with central heating, Data not shown in Table)[52], and (Average RH = 48.4% without and 34.4% with central heating, Data not shown in Table) [37]. A large multi-centre study, reported a lower likelihood of self-reported visible mould associated with central heating (*vs no central heating;* OR 0.72 (0.64--.81), Table 2.12), and with ducted air heating (*vs no central heating;* OR 0.65 (0.54-0.77), Table 2.12)[46], in univariate logistic regression analysis.

An interesting result from a study from Oceania showed that heating type had no impact on indoor self-reported visible mould, when looking at households where only one type of heating was used, including gas heating only, electric heating only and fireplace only. On the other hand, households that used multiple heater types had increased likelihood of reporting visible mould (OR 2.06 (1.09-3.90), Table 2.12), however, associations with (multiple types of) heating did not remain significant when adjusting for other household characteristics, including age of the home, local climate, and occupancy [41]. A similar observation was made in a study from Northern Europe, which found that the use of “additional heating” was associated with an increased likelihood of inspector-assessed signs of dampness indoors (Table 2.12)[22].

In a unique study from the UK, researchers looked at the age of the heating system, and found that it was associated with an increased likelihood of self-reported visible mould, after adjustment for other house characteristics including house age, house type and heater type (gas and boiler type) (*vs less than 5 years; heating system 5-10 years old* aOR 4.5 (2.1-9.8), and *greater than ten years* aOR 1.9 (1.2-3.4), Table 2.21)[47]. There is no evidence of continuous decline, as may be expected if this result were caused by the deterioration of the systems, pointing perhaps to residual confounding. In another related finding from the same study, households who chose not to heat due to cost had an increased likelihood of living in a house with indoor mould (see also above in “heating behaviours”); this variable was not adjusted for in the analysis with heater age and may be a potential confounder that could explain the association with age of the heating system.

Spengler et al., in a large survey from North America, reported that “wood heating” was not associated with self-reported signs of indoor dampness, while both unvented heaters, and use of a gas oven for heating were associated with an increased likelihood (Table 2.21).[36].

Two surveys from East Asia found associations with heating type and signs of indoor dampness. Kong et al., demonstrated increased likelihood of self-reported dampness indoors with “coal, wood or kang stove” compared to hot water radiator or underfloor heating (*vs hot water radiators; coal or Kang style stove* OR 1.9 (1.1-2.5), Table 2.12)[43]. The authors also reported that households with these same coal or kang style heating systems reported that their houses were colder than those with other styles (hot water radiator and underfloor heating), and also ventilated less frequently. Coal or Kang stoves were also more likely in detached houses and in houses without wall insulation [43]. Cai et al., reported that the use of electric heating (vs underfloor) was associated with an increased likelihood of self-reported water damage, but not mouldy odour, after adjusting for other house and household characteristics, including building age, ventilation behaviour and tenure (*vs no electric heaters*; aOR 1.65 (1.09-2.51), Table 2.12)[29], however this finding was only significantly associated in the 2019 and not in the 2010 survey.

Another large study also found positive associations between use of electric heaters and self-reported signs of dampness, compared to households with central heating, from Northern Europe (Table 2.12). These results were not adjusted for covariates [30].

2.10.1.5 Heating interventions

Four studies report the findings of heating interventions (improved heating), from the UK (3), and North America (1). All four reported post-intervention reductions in indoor standardised RH and inspector-assessed visible mould [24], inspector-assessed signs of indoor damp [65], and self-reported signs of indoor dampness [78, 79](Table 2.12). The study from Hopton et al., showed that participants post -intervention also reported significantly less “poor-repair” of their homes, and significantly more people choosing to heat the whole house post-intervention (as opposed to just part of the house), pointing to additional changes which may have influenced the large reduction seen in self-reported dampness [78].

Table 2.12 Heating and Temperature

(Reponen et al. 2013)STUDY	Number of houses	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
1989 Strachan D and Saunders C Edinburg, Scotland [74]	330	Inspection	heating bedroom -none ↑ -night only ↑ -heating bedroom day only↓ -day and night ↓	Adjusted mean RH	4
1997 Wickens K. et al New Zealand [52]	474*	Inspection and self-report	Vs no central heating -central heating ↓	Comparison of means	4
2006 Ceylan et al. Turkey [37]	242	Inspection	Vs no central heating -central heating ↓	Comparison of means	4
2006 Oreszczyn et al. UK [24]	3099	Inspection	**Living room** Vs satisfied with heating -dissatisfied with heating ↑ 2.90% (1.74-4.05) Vs pre-intervention -insulation only intervention ↓ NS -heating only intervention ↓ 1.90% (-3.69, -0.11) -heating + insulation ↓ -2.97% (-4.46, -1.49) **Bedroom** Vs satisfied with heating -dissatisfied with heating ↑ 5.27% (3.90, 6.65) Vs pre-intervention -insulation only intervention ↓ -2.46% (-4.37, -0.55) -heating only intervention ↓ -4.74% (-6.85, -2.63) -heating + insulation ↓ -6.40% % (-8.20, -4.71)	Regression of Standardised RH	5
2015 Boulic et al. New Zealand [77]	26	Inspection	Vs unflued gas heater Heat pump ↓	Comparison of means	3
2016 Fakanule et al. Nigeria [39]	132	Inspection	- higher temperature ↑	Spearman’s rank correlations	3
2017 Wang et al. Sweden [45]	605	Inspection	-higher temperature ↓	Correlation coefficient	5
2021 Psomas et al. Sweden [27]	1400	Inspection	-higher temperature ↓	Comparison of means	3
VISIBLE MOULD					
1989 Strachan D and Saunders C Edinburg, Scotland [74]	1000*	Inspection temp Self-report mould	- higher temperature ↓	Comparison of means	4
1989 Brunekreef B et al 6 U.S cities [58]	4625*	Self-report	-Heating system ↔	Comparison of means	2
1994 Spengler J. et al. USA and Canada36]	12842*	Self-report	-Use of oven for heating ↑	Multivariate regression (data not shown)	3
2002 Zock J-P et al 18 countries [46]	19218*	Self-report	Vs no central heating -Central heating ↓ OR 0.72 (0.64-0.81)	Univariate regression	4

			Vs no ducted heating -Ducted air heating ↓ OR 0.65 (0.54-0.77)		
2005 Howden-Chapman P et al New Zealand [41]	613	Self-report	-multiple types of heating ↑ OR 2.06 (1.09-3.90) Vs no heating -gas only heating ↔ -electric only ↔ -fireplace only ↔	Univariate regression	4
2006 Oreszczyn et al. UK [24]	3099	Inspection	Vs pre-intervention -heating only ↓ OR 0.54 (0.36-0.82) -heating & insulation ↓ OR 0.61 (0.43-0.85) vs heating satisfaction good -dissatisfied with heating ↑ OR 2.05 (1.55-2.70)	Multivariate regression	5
2007 Kercsmar et al. USA [65]	51*	Inspection	-heating/ventilation remediation ↓	Wilcoxen rank score	3
2010 Dales et al Prince Edward Island, Canada [21]	357	Inspection	-higher temperature ↓	Anova	4
2012 Keall et al New Zealand [50]	891	Inspection	-unflued gas heater ↔	Pearson's correlation coefficient	2
2015a Sharpe et al. UK [47]	671	self-report	**Univariate** Vs no gas heating -gas heating ↓ OR 0.7 (0.5-1.1) **Multivariate** -gas heating ↔ -age of heating system ↑ 5-10 years OR 4.5 (2.1-9.8) >10 years OR 1.9 (1.2-3.4) -inadequate heating ↑ OR 3.4 (2.0-5.8) Vs does use heating -do not use heater due to cost aOR 2.2 (1.5-3.2)	Multivariate regression	4
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1987 Martin CJ et al. Edinburgh [63]	300	Inspection	-unflued gas heater ↔	X^2 & Mann-Whitney U	3
1989 Platt SD et al Edinburgh, London and Glasgow [64]	597	Inspection	-Cold indoor temperature↑ -unflued gas heater ↔	X^2	3
1989 Brunekreef B et al 6 U.S cities [58]	4625*	Self-report	-Heating system ↔	Comparison of means	2
1990 Dales RE Canada [21]	14799*	Self-report	-unflued gas heater ↔ -Wood stove heating ↔	Comparison of means	2
1994 Spengler J. et al United States and Canada [36]	12842*	Self-report	-Unvented heaters ↑ -Use of gas oven for heating ↑ -Wood heating ↔	Univariate regression (data not shown)	3
1996 Hopton and Hunt. Scotland [78]	132	Self-report	-house too cold ↑ -post intervention ↓	McNamar test	3
1996 Williamson IJ et al Glasgow, Scotland. [20]	222	Inspection and Self-report	-Type of heating ↔	Univariate regression (data not shown)	3
1997 Wickens K. et al New Zealand [52]	474*	Inspection and Self-report	-Type of heating ↔	Comparison of means with p value	4
2001 Kipelnäinen et al. Finland [30]	10667*	Self-report	-heating electric ↑ (vs central or woodstove)	Comparison of means	2
2006 Haverinen-Shaughnessy et al. Finland [22]	363	Inspection	-additional heating ↑	Comparison of means	4
2007 Shortt et al. Northern Ireland [79]	100	Self-report	-post intervention ↓	X^2	2

2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	-Type of heating ↔ NS	X^2 for all data, and Multivariate regression for single family houses only	4
2012 Keall et al New Zealand [50]	891	Inspection	-unflued gas heater ↔	Pearson's correlation coefficient	4
2016 Lanthier-Veilleux, Genereux & Baron. Canada [34]	2097 Students	Self-report	-heating system ↔ -thermostat ↔	Univariate regression	3
2019 Kong et al. China [43]	7865	Self-report	**Bungalows** Vs hot water radiator -Coal or Kang heating ↑ aOR 1.9 (1.2-3.0)	Multivariate regression	3
2020 Cai et al. China [29]	8947	Self-report	-Electric heating ↑ Vs underfloor aOR 1.7 (1.1-2.5)	Multivariate regression	4
CONDENSATION					
1989 Strachan D and Saunders C Edinburg, Scotland [74]	1000*	Inspection & Self-report	-warmer temp ↓	Comparison of means t-test for significances and Multivariate regression (data not shown)	4
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	-Type of heating ↔ NS	X^2 for all data, and Multivariate regression for single family houses only	4
2019 Kong et al. China [43]	7865	Self-report	-Coal or Kang heating aOR 1.4 (1.0-1.9) ↑	Multivariate regression	3
MOULDY ODOUR					
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	-Type of heating ↔	X^2 for all data, and Multivariate regression for single family houses only	4
2017 Wang et al. Sweden [45]	605	Inspection	-higher temperature ↓ OR 0.86 per 1°C (0.75-0.99)	Multivariate regression	5
2019 Kong et al. China [43]	7865	Self-report	-Coal or Kang heating ↑ aOR 1.7 (1.1-2.6)	Multivariate regression	3

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.10.2 Discussion: Heating and Temperature

Studies that assessed heater type were consistent in showing no association with dampness and mould by type, except for the consistent finding of lower dampness indicators with central (vs no central) heating. On the other hand, when considering indoor temperature, every study but one (of seven), reported less dampness with increased temperature. This was true whether the temperature was measured, or described by participants, and across each of the dampness assessments included in this review. The opposite result reported by just one study, from Africa, may be explained by climatic differences. In particular, two studies that showed that higher indoor temperatures were associated with lower indoor RH were both from Northern Europe, and in both studies, temperature measurements were conducted in winter, while a result demonstrating the opposite was assessed in equatorial Africa (Nigeria). It has been demonstrated that increased window opening in winter in cold climates leads to reduced indoor RH [27], while the opposite may be true in humid equatorial climates (which do not have a defined heating season), as well as temperate and oceanic climates, due to the humidity of outdoor air.

Heating satisfaction and heating behaviour are likely to be related, and both are likely influenced by both heating type and SES in that an ineffective heater that is expensive to run would be unlikely to create a high degree of satisfaction (ie, “Can you afford to use the heater you have to get your house to a comfortable temperature?”). Hence, heating satisfaction may well indicate the likelihood of the household to use that heating system, suggesting this could be used as an indicator question.

More needs to be understood about the impact of heating practices, both in terms of time (all/part of the day) and in terms of space (all/part of the house), as these factors, which have been infrequently measured, appear to make material differences [74, 78].

2.11 Insulation, double glazing and energy efficiency

Twelve studies assessed insulation measures in relation to indoor dampness, from the UK (4), Oceania (3), East Asia (2) Northern Europe (2) and North America (1). First, insulation will be considered as present/absent or comparative assessments (e.g. “improved insulation”, insulation thickness etc.), in ceilings, walls or underfloor or as glazing. Then, results for studies that focused on insulation intervention and improvements will be discussed. Then other factors will be considered related to insulative capacity, including U-value, which is a measure of the overall insulative capacity of the building across all the building components, age of insulation and glazing, and wall cavities. Finally, results related to energy efficiency ratings will be discussed.

2.11.1.1 Insulation

Six studies, from the UK (3), Oceania (2), and East Asia (1), reported on associations between insulation (presence or amount) and dampness in cross-sectional studies. One study, from the UK, showed that thicker ceiling insulation was associated with lower (standardised) RH (*vs <100mm*; *100mm thick or greater* RH= -2.03% (-3.31, -0.76)) in the living room, and bedroom (*vs <100mm*; *100mm thick or greater* RH= -1.44% (-2.90, -0.01); Table 2.13)[24]. These values were adjusted for outdoor climate, year and region. The study also showed that less inspector-assessed visible mould was reported (*vs <100mm*; *100mm thick or greater* OR 0.66 (0.49-0.88), Table 2.13) in the whole house [24]. In agreement, a survey from Oceania reported an increased likelihood of self-reported visible mould in homes with no insulation (*vs any insulation*; aOR 1.84 (1.09-3.10)) using multivariate analysis adjusted for other house characteristics, including age and condition of the house, number of occupants and ventilation behaviours [41]. A second study from Oceania found no association between underfloor insulation and visible mould, but small but significant increases of both “a little damp” (Rho 0.12; Table 2.1) and musty odour (Rho 0.07; Table 2.13)[50]. The opposite was reported in a more recent study from the UK that matched administrative data on insulation install dates with survey results including self-reported visible mould. This study found that more roof space insulation was associated with more self-reported visible mould (*Vs < 250mm insulation; ≥ 250mm* OR 3.0 (1.7-5.4), Table 2.13)[47]. Wall cavity insulation (vs no cavity insulation), on the other hand, was associated with the expected reduced likelihood of visible mould in homes with wall cavity insulation (*vs none; presence of cavity wall insulation* OR 0.6 (0.4-0.9)[47]. Finally, a cross-sectional study from East Asia, which used multivariate analysis, adjusting for other house characteristics and occupant behaviours including heating system, ventilation system and building age, found (presence of) wall cavity insulation to be associated with a reduced likelihood of self-reported damp or mould spots in apartments (vs no wall insulation; OR 0.41 (0.23-0.74), Table 2.13); in bungalows (detached houses) a reduced likelihood of condensation was found (OR 0.5 (0.2-0.9), Table 2.13). No association between wall insulation and mouldy odour was observed (Table 2.13)[43]

2.11.1.2 Improved or post-intervention insulation

Three longitudinal studies reported on indoor dampness before and after insulation improvements, from the UK (2) and Oceania (1), and one cross-sectional study from North America reported associations with “improved insulation”. All four studies reported reduced signs of dampness post intervention, or in relation to insulation “improvements”. In the UK, Oreszczyn et al., reported results for a subset of participating households that received insulation intervention alone, and another group that received the insulation intervention alongside improved heating. Insulation only was associated with a significant reduction of standardised RH in bedrooms (-2.46% (-4.37, -0.55), Table 2.13), while houses that also received improved heating had higher reductions of RH (-6.40% (-8.20, -4.71))[24]. In living rooms, insulation alone was not significantly associated with RH, while insulation plus heating was associated with an estimated reduction of 2.97% standardised RH (95% confidence Intervals (-4.46, -1.49); Table 2.13)[24]. A study from Oceania found that RH in the main bedroom of intervention homes was reduced by 2.3%, compared to non-intervention houses, after adjusting for baseline measurements (-2.3% (-4.2, 3.0), Table 2.13)[66].

These same two studies also reported post-intervention reductions of inspector-assessed visible mould (*Vs none, mould anywhere in the house* OR 0.68 (0.47-0.98), Table 2.13), [24], self-reported visible mould (OR 0.24 (0.18-0.32), Table 2.13), and condensation (OR 0.16 (0.11-0.22), Table 2.13) [66].

The third intervention study, from the UK, reported reductions in self-reported signs of dampness (Table 2.13)[79]. And finally, a study form North America reported that "improved insulation" was associated with reduced frequency of self-reported signs of dampness [21]

2.11.1.3 Wall cavity

A wall cavity (without insulation) can act as an insulating building component. Results from Oreszczyn et al., showed that wall cavity construction was significantly associated with reduced RH in bedrooms (*vs solid wall construction;* -1.44% (-2.90, 0.01), Table 2.13), but no significant association was found for living rooms (Table 2.13). Cavity walls were also associated with lower likelihood of inspector-assessed visible mould (*vs solid wall construction*; OR 0.52 (0.40-0.68), Table 2.13)[24].

2.11.1.4 U-value

Two studies from Northern Europe reported on associations between U-value (insulating quotient) of the building as a whole. One showed that higher overall building U-value was associated with increased RH and moisture load (calculated from RH)[45]. The other study did not find that U-values, either of the whole house or of the windows only, were associated with RH categories (based on ranges of RH values)[27].

2.11.1.5 Age of insulation/glazing

Age of insulation and double glazing was assessed in one study, from the UK. As described above, there was no association reported with age of the insulation, but double glazing from 5-10 years of age was associated with increased likelihood of self-reported visible mould (OR 2.6 (1.1-5.9), Table 2.13), although there was no significant relationship with double glazing over ten years old (Table 2.13).

2.11.1.6 Energy efficiency rating

Two studies from the UK reported associations between energy efficiency ratings and dampness assessments. One study showed steady decreases in standardised RH in bedrooms with increasing energy efficiency ratings (*vs quartile 1*; *Q2* -2.36% (-4.15, -0.58); *Q3* -5.50% (-7.30, -3.69); *Q4* -6.73% (-8.57, -4.89), with similar, but smaller reductions in the living room (Table 2.13)[24].

Table 2.13 Insulation

STUDY	NUMBER	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
2006 Oreszczyn et al. UK [24]	3099	Inspection	**Living room** Vs solid wall construction -cavity wall ↓ (NS) Vs <100mm roof insulation -roof insulation ≥100mm ↓ -2.03% RH (-3.31, -0.76) Vs pre-intervention -insulation only intervention ↓ NS -heating + insulation ↓ -2.97% (-4.46, -1.49) Energy efficiency rating: Vs ≤41 (quartile 1) 42-46 (Q2) ↓ NS 57-69 (Q3) ↓ -3.63% (-5.14, -2.11) ≥70 (Q4) ↓ -4.41% (-5.96, -2.86) **Bedroom** Vs solid wall construction -cavity wall ↓ -1.44% (-2.90, 0.01) Vs <100mm roof insulation -roof insulation ≥100mm ↓ -3.67% (-5.24, -2.10) Vs pre-intervention -insulation only intervention ↓ -2.46% (-4.37, -0.55) -heating + insulation ↓ -6.40% (-8.20, -4.71) Energy efficiency rating: Vs ≤41 (quartile 1) 42-46 (Q2) ↓ -2.36% (-4.15, -0.58) 57-69 (Q3) ↓ -5.50% (-7.30, -3.69) ≥70 (Q4) ↓ -6.73% (-8.57, -4.89)	Standardised RH regression	5
2007 Howden-Chapman et al New Zealand [66]	1350	Inspection	-post insulation intervention ↓ -2.3% (-4.2, -3.0)	Adjusted RH	6
2017 Wang et al. Sweden [45]	605	Inspection	-higher building U-value ↑	Correlation coefficient	4
2021 Psomas et al. Sweden [27]	1400	Inspection	-higher building U-value ↔ -window U-value ↔	Comparison of means	2
MOISTURE LOAD					
2017 Wang et al. Sweden [45]	605	Inspection	-higher building U-value ↑	Correlation coefficient	4
VISIBLE MOULD					
2005 Howden-Chapman P et al New Zealand [41]	613	Self-report	Vs has insulation -No insulation ↑ aOR 1.84 (1.09-3.10)	Multivariate regression	3
2006 Oreszczyn et al UK [24]	3099	Inspection	vs solid concrete -cavity wall ↓ OR 0.52 (0.40-0.68) Vs <100mm roof insulation -roof insulation ≥100mm ↓ OR 0.66 (0.49-0.88) Vs pre-intervention -insulation only ↓	Multivariate regression	4

			OR 0.68 (0.47-0.98) -heating + insulation ↓ OR 0.61 (0.43-0.85) Energy efficiency rating: Vs ≤41 (quartile 1) 42-46 (Q2) ↓ OR 0.67 (0.49-0.93) 57-69 (Q3) ↓ OR 0.63 (0.45-0.88) ≥70 (Q4) ↓ OR 0.35 (0.23-0.51)		
2007 Howden-Chapman et al New Zealand [66]	1350	Inspection and Self Report	-Insulation intervention ↓ OR 0.24 (0.18-0.32)	Comparison of means with p values and Multivariate regression	3
2012 Keall et al New Zealand [50]	891	Inspection	Vs none -underfloor insulation ↔	Pearson's correlation coefficient	3
2015 Sharpe et al. UK [47]	671	Self-report and public records	Vs not greater that 250mm - loft insulation greater than 250mm ↑ OR 3.0 (1.7-5.4) Vs loft insulation ≤5 years -age of loft insulation greater than 5 years ↔ Vs no cavity wall insulation Cavity wall insulation ↓ OR 0.6 (0.4-0.9) Vs wall insulation ≤5 years -age of wall insulation 5-10 years ↔ -age of wall insulation >10 years ↔ Vs double glazing ≤5 years -double glazing 5-10 years old ↑ OR 2.6 (1.1-5.9) -double glazing >10 years old ↑ NS Energy efficiency rating: Vs rating >72: -65-72 ↑ OR 1.9 (1.1-3.4) -60-65 ↑ OR 3.8 (2.1-6.6) -<65 ↑ OR 2.7 (1.5-4.8)	Multivariate regression	2
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1990 Dales et al Canada [21]	14799*	Self-report	-Improved insulation↓	Comparison of means,	1
2007 Howden-Chapman et al New Zealand [66]	1350	Inspection and Self Report	-Insulation intervention ↓ OR 0.18 (0.13-0.24)	Comparison of means with p values, and Multivariate regression	3
2007 Shortt et al. Northern Ireland [79]	100	Self-report	-post intervention ↓	X^2	3
2012 Keall et al New Zealand [50]	891	Inspection	**A little damp** Vs none -underfloor insulation ↑ **Very damp** -underfloor insulation ↔	Pearson's correlation coefficient	3

2015 Liu et al China [38]	15 266 children 1-8yrs	Self-report	Vs single glazing -Double/triple glazing ↓ OR 0.79 (0.68-0.92)	Multivariate regression	3
2019 Kong et al. China [43]	7865	Self-report	**Apartments** Vs none -Wall insulation ↓ aOR 0.41 (0.23-0.74)	Multivariate regression	3
CONDENSATION					
2007 Howden-Chapman et al New Zealand [66]	1350	Inspection and Self-report	-Insulation intervention ↓ OR 0.16 (0.11-0.22)	Comparison of means and Multivariate regression	3
2019 Kong et al. China [43]	7865	Self-report	**Bungalows** Vs none -Wall insulation ↓ aOR 0.5 (0.2-0.9)	Multivariate regression	3
MOULDY ODOUR					
2012 Keall et al New Zealand 50]	891	Inspection	Vs none -underfloor insulation ↑ Rho 0.07	Pearson's correlation coefficient	3
2017 Wang et al. Sweden [45]	605	Inspection	Vs lower U-value - higher building U-value ↑ OR 1.27 (1.17-1.39)	Multivariate regression	4
2019 Kong et al. China [43]	7865	Self-report	**Bungalows & apartments** Vs none -Wall insulation ↔	Multivariate regression	3

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained)

2.11.2 Discussion: Insulation

Insulation is consistently associated with lower RH and less visible mould, signs of dampness and condensation. It is notable, however, that of the three studies that assessed mouldy odour, none reported significant reductions, with two reporting increases in mouldy odour associated with insulation and one finding no association. As discussed earlier, since musty or mouldy odour is the dampness indicator most strongly associated with respiratory health effects, including new-onset wheeze [5], it deserves particular attention. The study from Oceania reporting increased musty odour with underfloor insulation used unadjusted analysis (correlations), the study from Northern Europe reported that mouldy odour was associated with higher measured moisture (RH and moisture load), and higher U-value of the building, and associated with lower temperature and air exchange rate [45]. Interestingly, the authors reported that U-value was negatively correlated with temperature, in other words the houses with the highest insulating quotient were the coldest, which also points towards the potential for some confounding by heater use. The study from East Asia reported that generally the presence of wall insulation was associated with less dampness indicators, but the same was not found for mouldy odour. Unfortunately, this does not provide clarity, but the relationship between insulation and mouldy odour deserves more attention in future exposure assessment studies.

2.12 Ventilation

Thirty-four studies assessed ventilation in relation to indoor dampness assessments, from Northern Europe (13), North America (7), East Asia (5), Oceania (3), the UK (3), South-East Asia (2) and one multi-centre study (1).

2.12.1.1 Air-change rate

Five studies looked at associations with measures of air-change rate from Northern Europe (4) and North America (1). Two related studies from Northern Europe reported associations between air-change rate and moisture measurements. Both studies reported increased overall RH in houses categorised as having lower air-change rates (Table 2.14)[27, 45]. The study by Wang et al., also reported that houses categorised as having lower air-change rates (as originally assessed using tracer-gas methods) were associated with higher overall moisture load (calculated from RH)[45]. A study from North America assessed air-tightness in fifty-nine houses using tracer gas methods, and used those measures to simulate air-change rates taking into account weather conditions obtained from external weather-stations. They reported that air-change rate was negatively correlated with mean RH, but uncorrelated with visible mould area (Table 2.14)[16]; mean RH and mould area were uncorrelated. Another study from Northern Europe assessed air-change rate using tracer-gas, and reported that inspector assessed dampness problems were more likely in houses with low air-change rates and less likely in high air-change rated homes, when compared to the whole sample (*vs whole sample* OR 2.4 (1.25-4.44); *houses with dampness problems* OR 9.6 (1.05-87.45), Table 2.14)[80]. Another study from Northern Europe assessed air-change rate also using tracer gas. This study showed that absolute indoor humidity reduced with increasing air-change rate (Table 2.14), and that this association was not significantly moderated by ventilation system (natural, exhaust or balanced systems; data not shown)[81].

2.12.1.2 Ventilation system

Sixteen studies reported associations between indoor dampness assessments and type of ventilation system present in the home, from Northern Europe (7), North America (4), East Asia (2), South-East Asia (1), Oceania (1) and one multi-centre study (1). Five of these studies reported associations between ventilation type and moisture measurements from Northern Europe (3), North America (1) and Oceania (1). One study from Northern Europe conducted a comprehensive analysis of the influence of ventilation types on indoor humidity [81], a study that followed an earlier assessment from the same researchers in a smaller group of houses [82]. Emenius et al., assessed the effect of three types of ventilation systems (natural (opening windows), exhaust only, or balanced (exhaust with mechanical make-up air)) and showed that the type of system had only a minor effect on the association between indoor and outdoor humidity (with houses using natural ventilation slightly more humid) [81]. Across four consecutive survey periods, those participants reporting condensation most frequently, were more likely to have high indoor humidity and low air-change rate [81].

Both studies from this research group found that “natural” ventilation (i.e. the absence of a mechanical system and hence reliance on opening windows) was associated with very airtight buildings with the lowest number of air-changes per hour. This may not be comparable to other countries, such as New Zealand, where “natural” ventilation is more often associated with older style, draughty houses, with much higher air-change rates [83].

Another study from Northern Europe, by Hesselmar et al, also showed that ventilation type (natural vs mechanical) was not associated with RH [44]. In contrast, presence of mechanical ventilation was associated with lower indoor absolute air humidity in a third (but smaller) study from Northern Europe [84]. Another study, also small, from Oceania looked at the effect of installing positive pressure ventilation systems in 20 intervention houses, compared to 10 control houses. The authors reported reduced RH in homes with positive pressure ventilation units installed [85]. Finally, an intervention study in 51 homes in North America, undertook "weatherisation", an intervention package designed to reduce draughtiness and leaks, either with (intervention) or without (control) the addition of mechanical extract ventilation. The authors reported that moisture balance (the difference in vapour pressure inside vs outside) reduced in both intervention and control houses by similar levels [86].

One large, multi-centre study found less self-reported visible mould in homes with an extractor fan over the cooking stove (*vs no extractor fan*; OR 0.78 (0.70-0.90); Table 2.14)[46]. A similar result was shown for signs of self-reported dampness and kitchen fans in a large study from North America (Table 2.14)[36]. Another study, from Northern Europe, also found reduced self-reported dampness (in detached houses) with the presence of mechanical ventilation (*vs "natural" ventilation*; for floor moisture OR 0.51 (0.29-0.90), and for condensation OR 0.32 (0.22-0.47), Table 2.14)[31]. The same study showed balanced (supply and extract) ventilation was associated only with reduced likelihood of condensation (*vs "natural" ventilation*; OR 0.14 (0.24-0.62), Table 2.14), and type of ventilation system not with presence of a musty or mouldy odour (Table 2.14) [31]. A large multi-centre study from East Asia reported that natural ventilation was associated with increased self-reported condensation (*vs extract* *ventilation*; aOR 1.6 (1.0-2.7) Table 2.14) in multivariate analysis, adjusted for other house characteristics. The same study found no association with signs of dampness or mouldy odour (Table 2.14)[43]. Another large study from East Asia reported that the presence of a bathroom extract fan was associated with a reduced likelihood of self-reported signs of dampness (aOR 0.75 (0.62-0.92), Table 2.14), and mould odour (aOR 0.66 (0.54-0.81), Table 2.14), adjusted for other house characteristics including building age, type and size; no association was found with visible mould or condensation [38]. Finally, a study from North America reported that both a stove hood (cooking stove extract fan) (*vs no stove hood*; OR 0.52 (0.43-0.63) and bathroom ventilation (*vs no bathroom extract ventilation* OR 0.61 (0.44-0.63) Table 2.14) were associated with a reduced likelihood of self-reported signs of dampness. This study also reported reduced dampness with the presence of a central mechanical ventilation system (*vs no central mechanical ventilation system*; OR 0.52 (0.43-0.63) Table 2.14) and presence of an air conditioning unit (*vs no air conditioner*; OR 0.76 (o.61-0.85) Table 2.14), in unadjusted analysis [34].

2.12.1.3 Ventilation behaviour

Nine studies assessed dampness in relation to ventilation behaviours, from East Asia (5), the UK (2) and Oceania (2). One study reporting on window opening behaviours in relation to RH, found that opening windows at night was associated with slightly lower RH in children's bedrooms, however, when analyses were adjusted for heating and ventilation behaviours, the association disappeared (data not shown) [74]. A study from Oceania calculated ventilation scores from the answers to several questions about ventilation practices. This study showed lower scores (less ventilation) in homes with self-reported damp patches (*vs no damp patches*; 0.82 (0.70-0.97) *for each point score* *in the ventilation index*), condensation (*vs no condensation*; OR 0.88 (0.78-0.96), and visible mould (*vs no visible mould;* OR 0.80 (0.70-0.80), Table 2.14), using analyses adjusted for building age [87]. A study from East Asia reported dose-response association of increasingly less self-reported visible mould, for those opening windows sometimes, and often in spring in 2019 (*vs never; Sometimes aOR* 0.19 (0.09-0.38), *Often* aOR 0.13 (0.07-0.23); Table 2.14). Similar dose-response associations of less visible damp stains were observed in 2010 (*vs never; Sometimes aOR* 0.48 (0.32-0.74), *Often* aOR 0.34 (0.22-0.51)), and 2019 (*vs never; Sometimes aOR* 0.24 (0.10-0.61), Often aOR 0.20 (0.10-0.43)) and with condensation in 2019 (*vs never; Sometimes aOR* 0.40 (0.20-0.79), *Often* aOR 0.21 (0.12-0.38); Table 2.14), as shown in multivariate analysis, adjusting for building age and other house and household characteristics [29]. Two more studies from East Asia also showed that more frequent ventilation behaviours were related to less self-reported visible mould [88, 89].

Studies not finding an association between increased ventilation behaviour and lower indoor dampness include one from Oceania, which found that reported use of rangehood, extractor fans and window opening was not associated with self-reported visible mould (Table 2.15)[41]. A study from the UK found that houses of occupants who “ventilated to reduce dampness” had increased odds of self-reported visible mould (aOR 7.3 (3.9-13.2) Table 2.15), as were houses where people reported using an extractor fan while cooking (aOR 1.9 (1.3-2.8)) and those who used a bathroom extractor fan (aOR1.7 (1.2-2.4); Table 2.15), with all analyses adjusted for month, area and presence of insulation and double glazing [47].

Table 2.14. Ventilation

STUDY	HOUSES	Damp Self Report/ Inspection	REPORTED ASSOCIATIONS	STATISTICAL ANALYSIS TYPE	weight
RELATIVE HUMIDITY					
1989 Strachan D and Saunders C Edinburg, Scotland [74]	317	Inspection	-windows open at night ↓	Comparison of means and multivariate regression (data not shown)	4
1998 Lawton et al. Canada [16]	59	Inspection	-air change rate ↓	Correlation coefficient	3
1998 Emenius et al. Sweden [82]	59	inspection	Vs house with supply and exhaust (balanced) mechanical ventilation -natural ventilation ↑	X^2	3
2005 Hesselmar et al. Sweden [44]	109	Inspection	Vs house with mechanical ventilation -natural ventilation ↔	X^2	3
2010 Boulic et al New Zealand [84]	30	Inspection	-positive pressure ventilation ↓	Comparison of means Wilcoxen's rank tests	4
2017 Wang et al. Sweden [45]	605	Inspection	-lower air change rate ↑	Correlation coefficient	5
2021 Psomas et al. Sweden [27]	1400	Inspection	-lower air change rate ↑ -Pets ↑	Comparison of means	3
ABSOLUTE HUMIDITY					
1996 Dotterud et al Norway [84]	38	Inspection	-mechanical ventilation ↓	X^2 and fisher exact test And Relative risk	3
1998 Emenius et al. Sweden [82]	59	inspection	Vs house with supply and exhaust (balanced) mechanical ventilation -natural ventilation ↑	X^2	3
2004 Emenius et al. Sweden [81]	540*	Self-report and Inspection	-Air change rate ↓ -ventilation system ↔	Data not shown	3
OTHER HUMIDITY MEASUREMENTS					
2016 Francisco et al USA [86]	51	inspection	**Moisture balance (vapour pressure out:in)** --Weatherised to ASHRAE 62 ↓ (with no mechanical ventilation) -weatherised to ASHRAE 62.2 ↓ including addition of mechanical ventilation *Similar reductions in damp in both groups*	comparison of means	3
2017 Wang et al. Sweden [45]	605	Inspection	**Moisture load (AH out:in)** -lower air change rate ↑	Correlation coefficient	5
VISIBLE MOULD					
1998 Lawton et al. Canada [16]	59	Inspection	-air change rate & air leakage ↔	Comparison of means	3
2002 Zock J-P et al 18 countries [46]	19218*	Self-report	-Extractor fan over cooking ↓ OR 0.78 (0.71-0.85)	Multivariate regression	4
2005 Zhang et al. Australia [87]	996	Self-report	-increased ventilation ↓ OR 0.80 (0.70-0.90)	Multivariate regression	4
2005 Howden-Chapman P et al New Zealand [41]	613	Self-report	-dry clothes indoors ↔ -use of rangehood ↔ -use of extract fan ↔ -increased window opening ↔	Univariate regression	4
2010 Dales et al. Canada [21]	357	Inspection	-dogs ↔ -cats ↔ -other pets ↔	Anova	4/3
2014 Hu et al . China [88]	13335*	Self-report	-increased window opening ↓	X^2	3
2015 Lin et al. China [89]	4618*	Self-report	-low ventilation/cleaning ↑	X^2	2
2015a Sharpe et al. UK [47]	671	Self-report and public records	-ventilation to reduce damp ↑ aOR 7.3 (3.9-13.2) -use kitchen extractor ↑ aOR 1.9 (1.3-2.8)	Multivariate regression	4

			Use bathroom extractor ↑ aOR 1.7 (1.2-2.4) -cat ↑ aOR 1.8 (1.3-2.6) -dog ↑ aOR 1.9 (1.3-2.9) -dry washing indoors (yes) aOR 1.1.6 (1.1, 2.3)		
2020 Cai et al. China [29]	8947	Self-report	**Child's bedroom (2010)** Vs never -Open windows in spring (often) ↓ AOR 0.4 (0.2-0.7) **Child's bedroom (2019)** Vs never -Open windows in spring (sometimes) ↓ AOR 0.2 (0.1-0.4) -Open windows in spring (often) ↓ AOR 0.1 (0.1-0.2)	Multivariate regression	3
VISIBLE DAMPNESS & MOULD/WATER DAMAGE/FLOOR MOISTURE					
1989 Platt SD et al Edinburgh, London and Glasgow [64]	597	Inspection	-Pets ↔	X^2	4
1994 Spengler J. et al United States and Canada [36]	12842*	Self-report	-Kitchen fans ↓ -Use of air conditioner ↓	Multivariate regression (data not shown)	3
1996 Li C. et al. Taiwan [53]	1340*	Self-report	-Ventilation "fair" ↓ -Pets ↔	Comparison of means	3
1997 Yang et al. Taiwan [54]	4164*	Self-report	-Pets ↓	Comparison of means	3
1999 Oie L et al. Norway [80]	344	Inspection	vs whole sample OR 2.4 (1.25-4.44) -Low ventilation rates. ↑ OR 9.6 (1.05-87.45) -High ventilation rates ↔ NS	Multivariate regression	3
1999 Koskinen O et al Finland [40]	310	Inspection	-pets ↔	comparison of means	4
2001 Kipelnäinen et al. Finland [30]	10667*	Self-report	-Pets ↑	Comparison of means	2
2004 Emenius et al. Sweden [81]	540*	Self-report and Inspection	-Air change rate ↔	Data not shown	3
2005 Zhang et al. Australia [87]	996	Self-report	-increased ventilation ↓ OR 0.82 (0.70-0.97)	Multivariate regression	
2006 Haverinen-Shaughnessy et al. Finland [22]	363	Inspection	-natural ventilation ↑ -Dry washing indoors ↔	Comparison of means and Multivariate regression	4
2009 Hagerhed-Engman et al. Sweden [31]	8918	Self-report	-mechanical ventilation ↓ OR 0.51(0.29-0.90) -balanced ventilation ↔ NS	X^2 for all data and Multivariate regression for single family houses only	4
2013 Sun & Sundell. USA [35]	2819*	Self-report	Vs natural ventilation -air conditioning ↓ OR 0.58 (0.42-0.78)	X^2 and p values And Multiple regression	3
2014 Hu et al. China [88]	13335*	Self-report	-increased window opening ↓	X^2	3
2015 Liu et al China [38]	15 266*	Self-report	-bathroom exhaust fan ↓ OR 0.75 (0.62-0.92)	Multivariate regression	3
2015 Lin et al. China [89]	4618*	Self-report	-Low ventilation/cleaning ↑	Comparison of means and X^2 significance test	1
2016 Lanthier-Veilleux, Genereux & Baron Canada [34]	2097 Students	Self-report	-air conditioning ↓ OR 0.76 (0.61-0.85) Central mechanical ventilation ↓ OR 0.52 (0.43-0.63) -stovehood ↓ OR 0.61 (0.44-0.85)	Univariate regression	3

			-bathroom ventilation ↓ OR 0.61 (0.50-0.74)		
1997 Yang et al. Taiwan [54]	4164*	Self-report	-pets ↓	Comparison of means	2
2001 Kipelnäinen et al. Finland [30]	10667*	Self-report	-pets ↑	Comparison of means	2
2020 Cai et al. China [33]	8947	Self-report	Vs never -Open windows in spring (often) ↓ AOR 0.2 (0.1-0.4) -Open windows in spring (sometimes) ↓ AOR 0.2 (0.1-0.6)	Multivariate regression	3
2019 Kong et al. China [43]	7865	Self-report	-ventilation system ↔	Multivariate regression	4
CONDENSATION					
2005 Zhang et al. Australia [87]	996	Self-report	-increased ventilation ↓ OR 0.88 (0.78-0.96)	Multivariate regression	
2009 Hagerhed-Engman et al Sweden31]	8918	Self-report	Vs natural ventilation -mechanical ventilation ↓ OR 0.32 (0.22-0.47) -balanced ventilation ↓ OR 0.14 (0.24-0.62)	X^2 for all data And Multivariate regression for single family houses only	3
2013 Sun & Sundell. USA [35]	2819*	Self-report	Vs natural ventilation -air conditioning ↓ OR 0.66 (0.50-0.86)	X^2 and p values And Multivariate regression	3
2014 Hu et al .China [89]	13335*	Self-report	-increased window opening ↓	X^2	3
2015 Liu et al China [38]	15 266 children 1-8yrs	Self-report	-use of air conditioner ↔ NS -use of bathroom exhaust fan↔ NS	Multivariate regression	3
2019 Kong et al. China [43]	7865	Self-report	-Natural ventilation without extract fans ↑ AOR 1.6 (1.0-2.7)	Multivariate regression	4
2020 Cai et al. China [29]	8947	Self-report	**Child's bedroom (2010)** Vs never -Open windows in spring (often) ↓ AOR 0.6 (0.4-0.8) **Child's bedroom (2019)** Vs never -Open windows in spring (sometimes) ↓ AOR 0.4 (0.2-0.8) -Open windows in spring (often) ↓ AOR 0.2 (0.1-0.4)	Multivariate regression	3
MOULDY ODOUR					
2001 Engvall, Norrby and Norback. Sweden [62]	3241	Self-report and public records	-type of ventilation ↔	Not reported	1
2009 Hagerhed-Engman et al Sweden [31]	8918	Self-report	Vs natural ventilation -mechanical ventilation ↔ NS -balanced ventilation ↔ NS	X^2 for all data And Multivariate regression for single family houses only	3
2014 Hu et al China [88]	13335*	Self-report	-increased window opening ↔	X^2	3
2015 Liu et al. China [38]	15 266*	Self-report	-bathroom exhaust fan ↓ OR 0.66 (0.54-0.81)	Multivariate regression	3
2019 Kong et al. China [43]	7865	Self-report	-ventilation system ↔	Multivariate regression	4

OR = Odds Ratio, aOR = adjusted odds ratio, numbers in brackets are 95% confidence limits. *= number of individuals (number of houses not ascertained). ASHRAE 62 and 62.2 are ventilation standard (and addendum) for acceptable indoor air quality.

2.12.2 Discussion Ventilation

Although higher air-change rate, and increased ventilation behaviours were generally associated with lower RH and less indoor dampness and mould, the more highly engineered systems do not appear to be significantly better than simpler approaches such as extraction fans in the kitchen and bathroom, and increased use of open windows for ventilation.

Of five studies looking at mouldy/musty odour and ventilation, four found no association with type of system and one found less odour with increased window opening. Only one study reported a reduction in musty odour with use of a bathroom fan, while several studies reported that better ventilation was associated with lower levels of other dampness indicators but not mouldy odour [31, 43, 88]. The weakness of this association is important due to the fact that musty odour is the dampness indicator most strongly linked with causation of adverse health effects, and has been shown to be associated with new-onset wheeze in infants [5].

The unusual result from Sharpe et al., in the UK, with very high increased odds of visible mould in houses where the occupants “ventilate to reduce dampness” points to reverse causation, meaning that people may be ventilating *in response* to noticing dampness issues. This also highlights another important concept, that no matter how “good” ventilation behaviours are, they may not be able to alleviate the effect of serious problems which may be caused by other (non-behavioural) factors.

When comparing heating and ventilation in this review heating is more consistently associated with dampness outcomes than ventilation, although variability in assessments may impact the apparent effects. Few studies mutually adjusted for heating and ventilation in the same multivariate model, in one that did, neither were significant in adjusted analysis [41].

2.13 Synthesis and Conclusions

Characteristics which were demonstrated in this review to be consistently associated with indoor dampness parameters, and which should therefore be included in dampness exposure assessments include:

- **Occupancy**, for which a simple measure of the number of occupants per house appears sufficiently robust.
- **Indoor temperature**. Higher reported temperatures, whether monitored or self-reported by occupants, were consistently associated with less indoor dampness and mould. This important determinant of indoor dampness should be included in dampness exposure assessment protocols, to avoid confounding. Temperature monitors are widely available and relatively cheap, but in studies where it is considered too intrusive or labour intensive, this review shows that self-reported temperature assessment may be a useful alternative.
- **Air change rate**. A higher air change rate was consistently associated with less dampness. However, this is difficult to measure, even for those with expertise. Work to validate a standard survey question, or simple alternative protocol would be highly valuable.
- **External condition (poor repair).** This parameter was consistently associated, but few studies included this parameter in dampness exposure assessments. More attention is needed on the impact of poorly maintained building exteriors, as this is likely an important reason why older houses are often (although not always) found to be associated with indoor dampness. While poor repair is a modifiable characteristic, house age is not.
- **House level (in multi-storey buildings).** Although there was only a small amount of evidence here, it is consistent, and therefore should probably be

taken into consideration in studies considering exposure assessment of indoor dampness.

Characteristics which were demonstrated to be associated, but need the assessment procedures improved, as the relationships were somewhat inconsistent include:

- **House age**. This review suggests that age-related characteristics (design and construction materials and methods) may be modifiable determinants of indoor dampness, so collection of basic construction characteristics such as roof-style and window and cladding types and building age is worth attention in future indoor dampness exposure studies, and collecting information while house age may be acting as proxy for both these construction characteristics and poorer condition houses, this parameter may nevertheless help in identifying such associated characteristics.
- **Heating behaviour**. Better survey design for heating behaviour may contribute to improved understanding of the determinants of indoor dampness. This review showed that assessments which included the proportion or period of the day (i.e. morning, afternoon evening overnight, etc,) or the proportion of the house typically heated (i.e. central vs individual rooms), were consistently associated with dampness outcomes. Dissatisfaction with heating was also associated with more dampness, and may be a useful proxy of both heater use and effectiveness.
- **Ventilation**. While associations were generally consistent, showing that more ventilation generally improves indoor dampness, questions remain over optimal behaviours and minimum levels of ventilation for avoiding indoor dampness.

- **Insulation**. Some studies showed improvements (less dampness) with insulation, even without heating improvements, but this was inconsistent. Insulation alone, without effective heating may not be sufficient to improve indoor dampness.
- **Tenure/SES**. Associations with these parameters may be confounded by (attributable to) other characteristics shown here to be also associated with indoor dampness, including poorer external condition, higher occupancy and lower indoor temperatures. Studies considering this relationship should focus on the most effective modifiers of this effect, including landlord attributes (such as living nearby or at distance), and heating adequacy.

Characteristics which were consistently not associated with indoor dampness outcomes include

- **House type (apartment/detached etc.), and size.** Both of these categories may in fact be related to indoor dampness, but if this is the case, the effect appears to be less important, in general, than other determinants. If a survey included all the other important covariates discussed above, then an effect may show up. However, these other determinants should all be prioritised in exposure assessment.
- **Heater type.** Heater type was consistently unassociated with indoor dampness outcomes, except central heating which is consistently associated with less dampness in homes.
- **Moisture modifying appliances** including gas appliances, humidifiers and dehumidifiers were consistently unassociated with dampness and mould outcomes. Again, if these are related to indoor dampness, this review suggests

that the effect is less important (in general) than the other determinants described above.

A number of other potentially important, but somewhat speculative, issues are highlighted in this review, that may be worthy of attention to researchers undertaking exposure assessments of indoor dampness and mould.

1. Mouldy or musty odour is often not associated with the same house characteristics as other dampness indicators or measurements.

This is important, as without an understanding of the causal mechanisms, researchers looking at health effects are dependent on these indicators of dampness for exposure assessments. Mouldy or musty odour is consistently associated with negative health effects. The lack of evidence of reduced prevalence of musty or mouldy odour with both insulation and ventilation parameters is of particular concern, given that these are two of the most commonly recommended interventions to alleviate problems with dampness and mould. It may be that as mouldy and musty odour often have a lower reported prevalence than other dampness indicators, that many studies here lack statistical power to identify associations, however, several studies that showed a lack of association between ventilation and musty odour were large studies. A second issue potentially confounding these results was the use of self-reported dampness indicators. It may be that occupants become ‘acclimatised’ to the odours in their dwellings, and are therefore less likely to, or reliable in report(ing) them. More work to improve consistency in identification of household mouldy odours is warranted.

2. Condensation is often associated in the opposite direction to visible mould.

Where there was a lot of condensation, less visible mould was frequently seen, and vice versa. This pattern while not entirely systematic, was noticeable enough to warrant attention. Visible mould has been associated with cold indoor temperatures, while condensation occurs due to the indoor surfaces being warmer than outdoor temperatures, so this temperature differential could be one explanation. Moisture buffering is another possible explanation, which suggests moisture adsorbing into materials, may actually effectively reduce moisture in air sufficiently to reduce condensation – in which case the moisture is simply observed at one surface rather than another.

3. It is worth considering dampness in air (humidity) separately to moisture held in surfaces (floors, skirtings, wall materials).

Dampness in air can easily be remediated with ventilation (as long as outdoor air is drier, which it generally is). However, if moisture is held in the physical structure of the house, i.e., the framing and internal linings, then the moisture in indoor air may be continually replenished, and ventilation alone may not be sufficiently protective.

2.14 References

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3 House characteristics and condition as determinants of visible mould and musty odour: Results from three New Zealand House Condition Surveys in 2005, 2010 and 2015.

Phoebe Taptiklis, Robyn Phipps, Mark Jones, Jeroen, Douwes.

Published in Indoor Air31(3); 818-831 **(2021)**

3.1 Abstract

This study assessed associations between house characteristics and mould and musty odour, using data from three consecutive (2005, 2010 and 2015) New Zealand House Condition Surveys, involving a total of 1616 timber-framed houses. Mould, musty odour and house characteristics were assessed by independent building inspectors. We used multivariate logistic regression analyses mutually adjusted for other house characteristics for each survey separately. Positive and independent associations were found with tenure, ventilation, insulation, and envelope condition for both mould in living and bedrooms, and musty odour. In particular, we found significant dose-response associations with envelope condition, ventilation and insulation. Odds of mould increased 2.4-15.9 times (across surveys) in houses with the worst building envelope condition ($p<0.05$-0.001 for trend); optimal ventilation reduced the risk of mould by 60% and the risk of musty odour by 70-90% ($p<0.01$ for trend). Other factors associated with mould and musty odour included: tenure, with an approximate doubling of odds of mould across surveys; and insulation with consistent dose-response

patterns in all outcomes and surveys tested (p<0.05 for trend in two surveys with mould and one survey for odour). In conclusion, this study showed the importance of building envelope condition, ventilation and insulation to avoiding harmful damp-related exposures.

3.2 Introduction

Consistent associations between indoor damp and respiratory symptoms have been demonstrated, [1, 2] with indoor mould suggested to play a key role [3], although the specific underlying mechanisms remain largely unclear [4]. In addition to visible mould, the presence of musty and mouldy odour has also been associated with respiratory symptoms and rhinitis [5-7]. These dampness-related health effects present a major and avoidable cost to individuals' health and to the health care system, as demonstrated both in New Zealand [8] and internationally [9].

Evidence suggests that even small improvements in housing quality may have significant health benefits [10-12], but due to the complexity of the causes of indoor dampness, which are multi-factorial and frequently inter-related, it is unclear which specific improvements are most effective. Better understanding of the relative importance of the many contributing factors of indoor dampness is therefore needed, as this can guide more effective policies to reduce indoor dampness and mould, and resultant respiratory symptoms.

Significant positive associations with age of the house and visible mould [13-19] and mouldy odour [7, 18, 20] have been demonstrated, but this in itself provides few clues about effective interventions. Other house characteristics associated with indoor dampness and mould include the number of occupants, heating, ventilation, insulation, window construction, roof type, foundation type and house type [14-16, 19, 21-23].

An aspect that has been less extensively studied is the association between the condition of the exterior and indoor dampness and mould. Studies that focused on these issues have found consistent positive associations between poor repair and increased indoor mould [15, 22, 24]. However, these studies assessed poor repair only as a single overall rating, and only one of these studies had the maintenance condition rated by a building professional [24], with the other two studies [22, 24] relying on self-reporting. None of these studies further defined or characterised this poor repair rating, hence significant knowledge gaps remain.

The current study, using data from three consecutive House Condition Surveys in New Zealand conducted in 2005, 2010 and 2015, examined associations between a wide range of housing characteristics including an overall condition rating (OCR), and inspector-reported indoor mould and musty odour (both strongly associated with indoor dampness). No associations with health were assessed.

3.3 Methods

3.3.1 The New Zealand House condition Survey

The New Zealand House Condition Survey is conducted by BRANZ, a national building research body, approximately every five years since 1994 [25]. The study reported here used data collected in the three most recent surveys i.e., 2005, 2010 and 2015. The sampling methodology is described in detail elsewhere [25-28]. Briefly, the three surveys were restricted to single family, timber-framed dwellings (no apartments were included), with each survey involving an entirely new sample i.e., no houses were included in more than one survey. While using almost identical assessment tools, there were some differences between the three surveys, which are summarised in table 3.1. In particular, in 2005, the sample was limited to only owner-occupied houses in the three largest New Zealand cities and outlying regions: Auckland and Wellington in the North Island, and Christchurch in the South Island. Also, home inspectors (trained building professionals) worked within regions and no training specifically related to the survey was provided. In contrast, for the 2010 and 2015 surveys, rental houses and smaller rural towns were also included, and a sampling structure was developed to capture a representative sample of dwellings. This involved dividing the country into 13 strata, 11 of which corresponded to cities and the remaining two being the rest of the North Island, and the rest of the South Island. Cluster sampling was used within strata based on census mesh-blocks (smallest statistical area unit). Also, training for home inspectors was introduced, involving a day of theory, followed by supervised inspections. In 2010 inspectors travelled nationally, while in 2015, there were again regional survey teams.

3.3.2 House characteristics

The surveys included >1500 individual components, including presence of insulation, heaters and mechanical ventilation systems, site details such as location, slope of site, and exposure to noise, air pollution and sun. Other information collected included land and house value, number of occupants, year of construction and date of survey. Of these variables, 62 variables were selected as potentially associated to indoor dampness (see supplementary Table 1); apart from these 62 variables, no other variables were assessed. Inspection of wall cavities to assess the presence of insulation were conducted in the 2005 survey, but this was abandoned in later surveys due to practicality and health and safety concerns. In these cases, wall insulation was identified based on the house age and conversation with the occupants. Age of the house was identified and categorised as follows: pre 1930s/1930-1979/1980 and newer, with categories reflecting the broad shift towards increasing airtightness over time. Houses built prior to 1930 used almost exclusively strip floors, and often strip wall linings, and are the least airtight; from 1930, increasing use of plaster and sheet floor and wall materials increased airtightness; and 1979 marked the introduction of the first insulation regulations in new builds (roof-cavity only). Along with detailed records of material types for most of the building components, condition ratings on a 5-point scale (Excellent, Good, Moderate, Poor, Serious) were given for major components i.e., windows, doors, roof, gutters, subfloor ventilation, exterior paint condition, etc. These rating values were based on the inspectors' assessments of the urgency of any potential repair required. For the purpose of this analysis, rating variables were collapsed from a 5-point scale into a binary outcome: 0=Excellent/good and 1=Moderate/poor/serious.

3.3.3 Mould and musty odour

Visible mould was reported for each room in the house separately using a 5-point scale of mould severity (none (1), specks (2), patches (3), large patches (4), extensive (5)). For the purpose of the analyses, due to relatively low numbers in each of those five categories, we treated the living or bedrooms as having mould if at least one bedroom or living room had any visible mould (i.e., a single present (scores 2-5)/absent score (score 1). In addition to analysing mould in living and bedrooms separately, we also assessed mould present/absent anywhere in the house. Musty odour was recorded for the whole house and not for individual rooms. Inspectors' training (2010 and 2015 only) to assess mould involved using photographs to standardise the interpretation of severity. For the purpose of this study, we consider mould and musty odours markers of indoor dampness; therefore, when discussing some results we use the term indoor dampness.

3.3.4 Temperature and rainfall data, seasons and climate zone

Twenty-four-hour rainfall and maximum temperature were obtained for each house for a 30-day period prior to the date of the survey. Data was sourced from the National Climate database [29] from the weather station closest to the house (generally <10 km). Data were expressed as 30-day total rainfall (mm) and mean 30 daily maximum temperature (°C). To assess the effects of season and climate on mould and musty odour we also classified houses by climate zone (North, approximate latitudes 30-36°S; Mid, approximate latitude 36 -41°S; and South, approximate latitude 41-46°S), with each climate zone having different insulation requirements as recognised in the New Zealand building regulations, and by season that houses were inspected (spring, summer, autumn or winter). New Zealand has a temperate climate, where winter and spring are generally the coldest, and summer and early autumn the warmest and driest. Because of the strong impact of surrounding oceans, mean daily temperatures generally remain within a relatively narrow band of around 10°C throughout the year [30], and this differs somewhat from the most northern parts of the country, with a hotter more humid climate and mean daily temperatures of 18°C in summer and 12°C in winter, to the southern-most climate zone, with a cooler, drier climate, and mean daily temperatures ranging from 15°C in summer to 10°C in winter [30].

3.3.5 Data analyses

Analyses were conducted using STATA 15 (StataCorp LP, TX, USA) for each survey separately. Associations between home characteristics and mould and musty odour were assessed using logistic regression. For visible mould, multivariate models mutually adjusting for other factors, were developed by including variables that fulfilled one of two requirements: 1) in unadjusted analyses, associations were consistent and (borderline) statistically significant ($p \leq 0.1$) for that variable in two or more of the surveys; 2) consistent associations with mould were observed across all three surveys, and statistically significant ($p \leq 0.05$) in at least one. For musty odour, which was available for only two surveys, variables were included if they were consistently associated with the outcome variable and were significant ($p \leq 0.05$) in one of the two surveys. All models were further adjusted for surveyor (except 2005, as surveyor was highly correlated with climate zone, thus resulting in multi-collinearity), average 30-day rain (mm) and 30-day average maximum temperature (^{o}C).

In addition to considering individual factors, we conducted analyses involving aggregated variables by combining variables within the same domains. Prior to doing so, we checked for consistency of associations (negative or positive) for each individual variable. The aggregated variable for mechanical ventilation involved combining information on independently operated kitchen, bathroom and clothes dryer extraction fans into one variable with each fan used to control a particular moisture point source. For this purpose, we used a score of “1” for the presence and “0” for the absence of each of these ventilation types and this was summed for each house and subsequently used in the analysis (the total sum variable ranged from zero to three). For the insulation domain, the presence of roof, underfloor and wall cavity insulation were summed, resulting in a score ranging from zero (no insulation) to three (all three areas insulated). The subfloor domain summed the presence of ponding or leaks, insufficient subfloor ventilation, and lack of ground moisture barrier, again resulting in a combined score ranging from zero to three. The building envelope condition (BEC) domain summed moderate to serious condition of roof cladding, wall cladding, exterior paint, windows and spouting/guttering, with a combined score ranging from zero to five. These aggregate domains allowed dose-response relationships within each domain to be assessed. In the analysis, houses with a score of three were used as the reference category for the insulation domain, due to low numbers in the category with zero insulation. For all other aggregate variables, the houses with a combined score of zero were used as the reference category.

Finally, in addition to measuring associations using the BEC domain as described above, we also conducted analyses using the overall condition rating (OCR) provided by the assessors at the end of the survey as single summary condition for the house rated on a 3-point scale: well maintained, moderately maintained or poorly maintained. This was based on the assessors' judgement of all maintenance needed anywhere in the house to bring it to "as new" standard. Materials and fittings both inside and out, were included in the assessment, and the presence of mould was considered a condition in need of maintenance. A flow diagram detailing all analyses is included in Appendix 1.

Tests for trend were conducted by treating each categorical domain as a continuous variable in the identical model, and using the resultant p-value. Collinearity was tested for all models using variance inflation factors, and all scores were under 3. Correlations between two variables were assessed using Spearman correlation tests.

3.4 Results

3.4.1 Sample characteristics

The age distribution of the houses in the three samples was similar with around half of the houses (52%-55%) built between 1930-1979, around a third (30%-36%) built after 1979, and 11%-15% built before 1930. Houses with three to four bedrooms, and metal roof cladding were more common (Table 3.2). Houses in the 2010 and 2015 surveys, which included rental properties, were more likely to have fewer bedrooms and occupants compared to 2005, and there was a slightly higher proportion of rental houses in the 2015 survey i.e., 27% compared to 22% in 2010. The three surveys also differed in terms of climate zone with the 2005 survey including more houses in the northern (warmest; sub-tropical) climate zone. The 2010 survey was the only one of the three to conduct the bulk of surveys in the colder, wetter months of winter and spring (Table 3.22). These differences in season of inspection were reflected in the weather data, with significantly more houses in the highest rainfall category and the lowest temperature category in the 2010 survey (Table 3.2).

Table 3.1. Differences between the three house condition surveys

	2005	***2010***	***2015***
Data collection differences			
Musty odour	-	Y	Y
Tenure	-	Y	Y
Floor area	Y	Y	-
Heating behaviour	-	-	Y
Methodology differences			
Surveyor (n)	6	7	15
Surveyor area	Regional (3 regions)	national	Regional (13 regions)
Survey training	-	Y	Y

Table 3.2: Sample and home characteristics of the three house condition surveys

	2005 (565 houses) n (%)	2010 (491 houses) n (%)	2015 (560 houses) n (%)
Visible Mould (living & bedroom)			
None	543 (96)	419 (85)	458 (82)
Specks	12 (2)	31 (6)	42 (8)
Patches	6 (1)	24 (5)	38 (7)
Large patches	1 (0.5)	13 (3)	16 (3)
Extensive	3(0.5)	4 (1)	6 (1)
Musty odour			
No	-	439 (89)	524 (94)
Yes		52 (11)	36 (6)
Survey season			
Summer (December-February)	540 (96)	50 (10)	172 (31)
Autumn (March-May)	10 (2)	-	149 (27)
Winter (June-August)	-	56 (12)	1 (0)
Spring (September-November)	15 (3)	383 (78)	238 (43)
30-day rain			
0-50mm	302 (53)	206 (42)	308 (56)
51-100mm	212 (38)	104 (21)	199 (36)
101-150mm	44 (8)	70 (14)	41 (7)
151mm or more	7 (1)	107 (22)	6 (1)
30-day temp (average)			
<15°C	0	177 (36)	48 (9)
15.1-20°C	183 (32)	260 (53)	233 (42)
20.1-25°C	315 (56)	49 (10)	229 (41)
>25°C	67 (12)	1 (0.2)	47 (8)
Climate zone			
North	304 (54)	161 (33)	183 (33)
Mid	111 (20)	227 (46)	159 (28)
South	150 (26)	101 (21)	218 (39)
Age category			
Pre 1930	87 (15)	58 (13)	62 (11)
1930-1979	307 (55)	242 (52)	294 (53)
1980 and older	167 (30)	163 (35)	204 (36)
Overall Condition Rating (OCR)			
Well maintained	280 (50)	125 (25)	243 (44)
Reasonably maintained	195 (35)	127 (26)	220 (39)
Poorly maintained	85 (15)	112 (23)	96 (17)
Missing	5 (1)	127 (26)	
Tenure			
Rented	-	108 (22)	149 (27)
Owner occupied	565 (100)	383 (78)	411 (73)
Occupants			
1 to 2	273 (48)	277 (56)	336 (60)
3 to 4	213 (38)	167 (34)	175 (31)
5 or more	63 (11)	47 (10)	49 (9)
Missing	16 (3)		
Bedrooms			
1 to 2	35 (6)	74 (15)	104 (19)

3 to 4	489 (87)	392 (80)	422 (75)
5 or more	41 (7)	23 (5)	32 (5.5)
Missing			2 (0.5)
Foundation Type			
Piles	321 (57)	314 (64)	339 (60)
Concrete slab	148 (26)	137 (28)	207 (37)
Mixed foundations	96 (17)	40 (8)	14 (3)
Cladding Type			
Timber weatherboard	186 (33)	97 (20)	128 (23)
Fibre cement	55 (10)	43 (9)	66 (12)
Brick	86 (15)	61 (12)	110 (20)
Mixed/other	238 (42)	290 (59)	256 (46)
Roof Type			
Metal roof	372 (66)	287 (58)	409 (73)
Concrete/clay tiles	183 (32)	201 (41)	121 (22)
Other	10 (2)	3 (1)	30 (5)

The proportion of houses with mould in living and bedrooms differed across the three surveys with 4% in 2005, 15% in 2010 and 18% in 2015. Musty odour was detected in 11% and 6% of houses in 2010 and 2015, respectively (Table 3.2).

3.4.2 Associations with mould

Tenancy was associated with mould in living and bedrooms in both surveys that included rental properties, statistically significant in the 2010 survey (aOR 2.1; $p<0.05$) and borderline statistically significant in the 2015 survey (aOR 1.7 $p<0.1$). Presence of extract ventilation in the bathroom, was associated with reduced living and bedroom mould, reaching statistical significance in the 2015 survey (aOR 0.6; $p<0.05$) and borderline statistical significance in the 2010 survey (aOR 0.5, $p<0.1$). Other home characteristics that were consistently associated with mould in the living and bedroom across the three surveys include: missing or leaking flashings on windows or doors (aORs 2.0-3.9, significant in 2010, $p<0.05$), poor window condition (aORs 1.7-3.4, significant in 2005, $p<0.05$) and number of occupants (≥5; aORs 1.1-5.1, significant in 2005 $p<0.01$; Table 3.3).

Table 3.3: Multivariate analysis of visible mould in living and bedrooms and musty odour in three house condition surveys

	Mould									Musty Odour					
			2005			**2010**			**2015**			**2010**			**2015**
			N/n = 545/22			N/n = 486/72			N/n = 526/101			N/n = 487/52			N/n = 520/34
			P=0.0001			P=0.0000			P=0.0000			P=0.0000			P=0.0000
			$R^2 = 0.26$			$R^2 = 0.25$			$R^2 = 0.26$			$R^2 = 0.35$			$R^2 = 0.43$
	N	*n*	aOR	*N*	*n*	aOR	*N*	*n*	aOR	*N*	*n*	aOR	*N*	*n*	aOR
Age of house															
Pre 1930	*84*	*5*	*Ref*	*56*	*7*	*Ref*	*61*	*13*	*Ref*	*57*	*11*	*Ref*	*59*	*4*	*Ref*
1930-1979	*300*	*16*	1.0 (0.3, 3.5)	*242*	*42*	1.8 (0.6,5.2)	*278*	*58*	0.8 (0.4, 1.9)	*242*	*34*	0.5 (0.2,1.5)	*277*	*28*	1.0 (0.2,5.6)
Post 1980	*161*	*1*	*0.1 (0.01,1.6)^*	*160*	*17*	2.5 (0.7, 9.4)	*187*	*30*	1.2 (0.5, 3.2)	*160*	*4*	0.3 (0.1, 2.1)	*184*	*2*	0.2 (0.0, 2.1)
Missing/mixed				*28*	*2*	0.6 (0.1, 3.8)				*28*	*3*	0.4 (0.1, 2.4)			
Climate zone															
North			(not included in model)	*159*	*23*	*Ref*	*170*	*40*	*Ref*						
Mid				*226*	*32*	**0.4 (0.1, 0.9)***	*147*	*40*	1.5 (0.2, 11.8)			-			-
South			§	*101*	*17*	0.7 (0.2,2.0)	*209*	*21*	0.4 (0.1,2.3)						
Occupants															
1 to 2	*272*	*8*	*Ref*	*272*	*35*	*Ref*	*314*	*69*	*Ref*						
3 to 4	*210*	*6*	0.8 (0.3, 2.6)	*167*	*29*	1.0 (0.5, 1.8)	*164*	*31*	0.9 (0.5, 1.7)			-			-
5 or more	*63*	*8*	**5.1 (1.6, 16.1)****	*47*	*8*	1.2 (0.4, 3.2)	*48*	*11*	1.1 (0.4, 2.8)						
Tenure															
owner occupier	*545*	*22*		*378*	*46*	*Ref*	*384*	*62*	*Ref*	*379*	*33*	*Ref*	*379*	*22*	*Ref*
tenant	*0*	*0*	*NA*	*108*	*26*	**2.1 (1.0, 4.4)***	*142*	*39*	*1.7 (1.0, 3.1)^*	*108*	*19*	**3.1 (1.2, 7.8)***	*141*	*12*	0.8 (0.3, 2.5)
Open fireplace															
No										*444*	*37*	*Ref*	*492*	*30*	*Ref*
Yes			-			-			-	*43*	*15*	**7.6 (2.7, 21.8)*****	*28*	*4*	3.0 (0.5, 17.6)
Range hood															
No	*329*	*18*	*Ref*	*194*	*42*	*Ref*	*195*	*53*	*Ref*	*195*	*33*	*Ref*	*194*	*29*	*Ref*
Yes	*216*	*4*	0.4 (0.1, 1.4)	*292*	*30*	0.6 (0.3, 1.1)	*331*	*48*	0.7 (0.4, 1.2)	*292*	*19*	0.5 (0.2, 1.3)	*326*	*5*	**0.1 (0.0, 0.3)*****
Bathroom ventilation															
None	*387*	*19*	*Ref*	*292*	*52*	*Ref*	*242*	*66*	*Ref*	*292*	*40*	*Ref*	*241*	*22*	*Ref*
Vented to outside	*158*	*3*	0.6 (0.2, 2.5)	*194*	*20*	*0.5 (0.3, 1.1)^*	*257*	*34*	**0.6 (0.3, 1.0)***	*195*	*20*	0.7 (0.3, 1.6)	*253*	*10*	0.7 (0.2, 2.2)
missing							*27*	*1*	0.2 (0.0, 2.0)				*26*	*2*	0.9 (0.1, 9.9)
Sufficient subfloor ventilation															
Yes	*156*	*12*	*Ref*	*74*	*9*	*Ref*	*94*	*29*	*Ref*	*75*	*7*	*Ref*	*93*	*9*	*Ref*
No	*259*	*8*	**0.3 (0.1, 0.9)***	*242*	*44*	1.5 (0.6, 4.0)	*219*	*41*	**0.4 (0.2, 0.7)*****	*242*	*38*	1.1 (0.3, 3.7)	*218*	*20*	1.0 (0.3, 3.4)
Slab foundation	*130*	*2*	0.7 (0.1, 4.1)	*170*	*19*	1.1 (0.4, 3.4)	*213*	*31*	**0.4 (0.2, 0.9)***	*170*	*7*	0.9 (0.2, 3.8)	*209*	*5*	0.3 (0.1, 1.8)
Roof condition rating															
Excellent/Good	*400*	*16*	*Ref*	*287*	*30*	*Ref*	*297*	*41*	*Ref*	*288*	*18*	*Ref*	*293*	*12*	*Ref*
Moderate/poor	*145*	*6*	0.4 (0.1, 1.5)	*171*	*37*	*1.9 (1.0, 3.7)^*	*229*	*60*	0.7 (0.3, 1.4)	*171*	*30*	1.5 (0.7, 3.5)	*227*	*22*	1.4 (0.3, 5.5)
Missing				*28*	*5*	2.6 (0.7, 9.9)				*28*	*4*	*4.4 (0.9, 21.6)^*			
Missing/leaking flashings															
No	*508*	*19*	*Ref*	*467*	*62*	*Ref*	*502*	*92*	*Ref*	*467*	*49*	*Ref*	*496*	*31*	*Ref*
Yes	*37*	*3*	2.7 (0.6, 12.3)	*19*	*10*	**3.9 (1.3, 12.2)***	*24*	*9*	2.0 (0.7, 5.8)	*20*	*3*	1.5 (0.3, 7.3)	*24*	*3*	0.5 (0.1, 3.2)
Window condition															
Excellent/Good	*368*	*16*	*Ref*	*249*	*22*	*Ref*	*292*	*27*	*Ref*	*249*	*11*	*Ref*	*288*	*9*	*Ref*
Moderate/poor	*177*	*6*	**3.4 (1.1, 11.2)***	*223*	*47*	1.8 (0.8, 3.7)	*230*	*73*	1.7 (0.8, 3.7)	*224*	*40*	*2.2 (0.9, 5.8)^*	*228*	*24*	1.0 (0.2, 4.2)
Missing				*14*	*3*	2.3 (0.5, 11)	*4*	*1*	4.2 (0.2, 78.2)	*14*	*1*	0.2 (0.0, 3.3)	*4*	*1*	*52.4 (0.9, 2998.3)^*

Wall cladding paint deterioration															
No	*273*	*8*	*Ref*	*366*	*46*	*Ref*	*367*	*56*	*Ref*	*367*	*37*	*Ref*	*363*	*12*	*Ref*
Yes	*272*	*14*	1.2 (0.5, 3.4)	*120*	*26*	0.9 (0.4, 1.8)	*159*	*45*	1.4 (0.7, 2.6)	*120*	*15*	1.1 (0.4, 2.7)	*157*	*22*	2.3 (0.7, 8.3)
Wall cladding condition															
Excellent/Good	*397*	*12*	*Ref*	*128*	*5*	*Ref*	*306*	*38*	*Ref*	*128*	*8*	*Ref*	*302*	*7*	*Ref*
Moderate/poor	*148*	*10*	1.0 (0.4, 3.2)	*339*	*64*	**4.1 (1.4, 11.9)****	*220*	*63*	1.3 (0.6, 2.7)	*340*	*42*	1.0 (0.3, 3.1)	*218*	*27*	**5.7 (1.3, 25.2)***
Missing				*19*	*3*	*4.6 (0.8, 27.3)^*				*19*	*2*	1.9 (0.2, 16.9)			
Cladding type															
Timber weatherboards										*95*	*16*	*Ref*	*119*	*8*	*Ref*
Fibrecement			-			-			-	*43*	*5*	**4.7 (1.0, 22.4)***	*59*	*7*	**6.1 (1.1, 33.0)***
Brick										*59*	*8*	0.8 (0.2, 3.4)	*104*	*5*	**14.3 (1.8, 111.6)****
Mixed/other										*290*	*23*	1.0 (0.4, 2.5)	*238*	*14*	2.6 (0.7, 9.8)
Spouting condition															
Excellent/good	*435*	*13*	*Ref*	*307*	*40*	*Ref*	*329*	*40*	*Ref*	*308*	*20*	*Ref*	*325*	*12*	*Ref*
Moderate/poor	*110*	*9*	*2.7 (0.9, 7.9)^*	*143*	*29*	0.7 (0.4, 1.4)	*197*	*61*	*2.1 (0.9, 4.6)^*	*143*	*28*	1.9 (0.8, 4.5)	*195*	*22*	2.5 (0.6, 10.2)
Missing				*36*	*3*	0.5 (0.1, 2.4)				*36*	*4*	1.0 (0.2, 4.4)			

N= number of houses in subgroup, n= number of houses in subgroup affected with mould/musty odour; § perfectly explains failure; ^p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001; NA data not available; - not associated in univariate analysis. All models adjusted for surveyor (except 2005 because of collinearity with zone), 30-day rain (mm), 30-day mean high temperature (°C) & wall insulation. Musty odour only, also adjusted for leaking plumbing indoors, ponding and leaks under house, dryer ventilation & window material.

When analysing the summed aggregate variables, we found a dose-response association for insulation ($p<0.05$ for trend, 2005 and 2015), with fewer types of insulation (roof, walls and underfloor) associated with increased odds of visible mould (aORs 2.3-11.4, for homes with no insulation compared to those with all three types of insulation; Table 3.4). Similarly, for aggregate building envelope condition (BEC) defects, we found a clear positive dose-response association across all surveys ($p<0.05$-0.01 for trend), with aORs for the largest number of defects ranging from 2.4-4.3 ($p<0.05$) when compared to houses with the fewest defects. A consistent dose-response association ($p<0.01$ for trend, all surveys) was also shown for ventilation (kitchen, bathroom and clothes dryer ventilation), with the presence of more types of ventilation associated with a 60-80% reduced likelihood of indoor mould (Table 3.4). Using the inspectors' overall condition rating (OCR), we found similar, but more pronounced, dose-response associations compared to our BEC rating, ($p<0.01$-0.001 for trend), with poor condition ratings increasing the risk of mould 8-16 times ($p<0.01$; Table 3.4).

Table 3.4. Analysis of aggregated variables and visible mould in living and bedrooms and musty odour in three house condition surveys.

	Mould									Musty Odour					
			2005 N/n = 549/22 P =0.0002 R^2 = 0.20			**2010** N/n = 486/72 P = 0.0000 R^2 = 0.18			**2015** N/n = 527/101 P = 0.0000 R^2 = 0.26			**2010** N/n = 486/52 P = 0.0000 R^2 = 0.25			**2015** N/n =4 94/34 P = 0.0000 R^2 = 0.31
	N	*n*	aOR	*N*	*n*	aOR	*N*	*n*	aOR	*N*	*n*	aOR	*N*	*n*	aOR
Climate zone															
North	304	18	(not included in model)	159	23	*Ref*	171	40	*Ref*	159	16	*Ref*	157	10	*Ref*
Mid	111	4		226	32	0.5 (0.2, 1.2)	147	40	1.0 (0.2, 6.3)	226	26	0.5 (0.2, 1.3)	142	16	1.1 (0.0, 64.9)
South	150	0	§	101	17	0.6 (0.2, 1.6)	209	21	0.7 (0.1, 3.1)	101	10	0.4 (0.1, 1.2)	195	8	0.8 (0.0, 33.3)
trend			NA			NS			NS			NS			NS
Occupants															
1 to 2	273	13	*Ref*	272	35	*Ref*	315	59	*Ref*	272	27	*Ref*	295	18	*Ref*
3 to 4	213	15	0.9 (0.3, 2.8)	167	29	1.1 (0.6, 2.0)	164	31	1.0 (0.6, 1.9)	167	22	1.2 (0.6, 2.5)	152	12	2.0 (0.8, 5.1)
5 or more	63	11	**4.7 (1.6, 14.5)****	47	8	1.3 (0.5, 3.4)	48	11	1.3 (0.5, 3.2)	47	3	0.5 (0.1, 1.9)	47	4	1.2 (0.3, 4.8)
trend			P<0.05			NS			NS			NS			NS
Tenure															
owner occupier	549	22		378	46	*Ref*	385	62	*Ref*	378	33	*Ref*	357	22	*Ref*
tenant	0	0	-	108	26	*1.8 (0.9, 3.6)^*	142	39	**2.1 (1.2, 3.9)***	108	19	*2.0 (0.9, 4.2)^*	137	12	1.5 (0.6, 4.0)
Ventilation/3 (kitchen/bathroom/clothes dryer)															
0	239	13	(not included in model)	142	35	*Ref*	132	40	*Ref*	142	26	*Ref*	132	19	*Ref*
1	188	9		168	20	**0.4 (0.2, 0.8)****	172	36	0.8 (0.4, 1.4)	168	18	*0.5 (0.2, 1.1)^*	172	13	0.6 (0.2, 1.5)
2	113	0	§	142	14	**0.4 (0.2, 0.8)****	190	23	**0.4 (0.2, 0.8)****	142	7	**0.3 (0.1, 0.9)****	190	2	**0.1 (0.0, 0.6)****
3	25	0	§	34	3	**0.2 (0.0, 0.8)***	33	2	0.3 (0.1, 1.5)	34	1	*0.1 (0.0, 1.2)^*			§
trend			NA			P<0.01			P<0.01			P<0.01			P<0.01
Insulation/3 (ceiling/underfloor/wall cavity)															
3	206	5	*Ref*	144	13	*Ref*	118	9	*Ref*	144	5	*Ref*	105	3	*Ref*
2	149	11	**6.1 (1.2, 31.6)***	185	32	1.4 (0.6, 3.1)	311	65	2.0 (0.8, 5.0)	185	18	2.3 (0.7, 7.3)	298	21	1.0 (0.2, 4.7)
1	167	17	**7.3 (1.2, 44.4)***	151	26	1.5 (0.6, 3.6)	90	24	**3.2 (1.1, 9.8)***	151	28	**4.5 (1.4, 14.8)****	83	7	0.5 (0.1, 3.0)
No insulation	27	6	**11.4 (1.4, 96.4)***	6	1	2.3 (0.2, 25.8)	8	3	3.5 (0.5, 25.5)	6	1	**15.7 (1.3, 195.6)***	8	3	5.0 (0.5, 48.3)
trend			P<0.05			NS			P<0.05			P<0.01			NS
Subfloor/3 (ponding or leaks/absence of ground cover/insufficient ventilation)															
0	182	8	*Ref*	27	3	*Ref*	210	32	*Ref*	27	1	*Ref*	195	5	*Ref*
1	189	19	0.6 (0.2, 2.0)	388	48	1.4 (0.4, 5.5)	140	32	1.0 (0.5, 2.0)	388	37	3.0 (0.4, 26.1)	135	11	2.2 (0.6, 8.0)
2	156	10	0.2 (0.1, 1.1)^	71	21	2.2 (0.5, 9.7)	154	30	0.7 (0.3, 1.4)	71	14	3.5 (0.4, 33.6)	142	13	2.1 (0.6, 7.4)
3	22	2	0.2 (0.0, 2.9)				23	7	0.5 (0.1, 1.9)				22	5	**6.1 (1.0, 37.0)***
trend			P=0.05			NS			NS			NS			NS
BEC/5 (Poorer condition of; roof cladding/wall															

cladding/windows/exterior paint/spouting and guttering)															
0-1	*319*	*8*	*Ref*	*156*	*13*	*Ref*	*236*	*25*	*Ref*	*156*	*5*	*Ref*	*221*	*3*	*Ref*
2-3	*170*	*16*	**3.0 (1.0, 8.8)***	*161*	*26*	1.5 (0.7, 3.3)	*137*	*24*	1.5 (0.7, 3.1)	*161*	*21*	**3.3 (1.1, 9.8)***	*124*	*11*	**9.1 (1.9, 44.1)****
4-5	*60*	*15*	**4.9 (1.3,19.0)***	*85*	*22*	**2.4 (1.0, 6.1)***	*154*	*52*	**2.6 (1.1, 5.9)***	*85*	*15*	**4.3 (1.3, 14.2)***	*149*	*20*	**15.9 (3.5, 71.5)*****
Missing				*84*	*11*	1.6 (0.6, 4.1)				*84*	*11*	**3.7 (1.1, 12.5)***			
trend			P=0.01			P<0.05			P<0.05			P<0.01			P<0.001
Overall Condition Rating (OCR)															
Excellent	*274*	*3*	*Ref*	*123*	*2*	*Ref*	*237*	*17*	*Ref*	*156*	*3*	*Ref*	*215*	*1*	*Ref*
Moderate	*186*	*9*	**4.0 (1.0, 15.6)***	*127*	*14*	**4.7 (1.0, 22.2)***	*218*	*44*	**2.8 (1.3, 5.9)****	*161*	*8*	2.4 (0.6, 10.4)	*206*	*11*	**16.7 (1.8, 153.1)****
Poor	*89*	*10*	**8.0 (1.9, 33.3)****	*111*	*38*	**15.6 (3.3, 72.8)*****	*95*	*40*	**8.0 (3.2, 19.8)*****	*85*	*40*	**23.8 (5.7, 98.1)*****	*95*	*22*	**67.9 (7.0, 657.6)*****
Missing				*125*	*8*	**8.4 (1.7, 40.8)****				*84*	*1*	0.4 (0.0, 4.4)			
trend			P<0.01			P=0.001			P<0.001			P<0.001			P<0.001

N= number of houses in subgroup, n= number of houses in subgroup affected with mould/musty odour. § perfectly explains failure; ^p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001; NS non-significant; - data not available. All models adjusted for surveyor (except 2005), 30-day rain (mm) and 30-day mean high temperature (C

In addition to considering mould in the living and bedroom, we also assessed associations with reported mould anywhere in the house. Age of the house was associated with mould in the whole house (aORs 0.3-0.8 for houses built in 1980 or later; Table 3.5), although this was significant only in 2015 (p<0.01). The apparent protective effect of bathroom fans was more pronounced compared to the relationship with living and bedroom mould (aORs 0.8-0.4, significant in 2010 and 2015, p<0.05-0.001), while the reduction in odds of mould related to presence of a range hood (extraction fan over cooker) (aORs 0.9-0.7, p<0.1 in 2015) was less pronounced. The individual factors making up the BEC domain (window, wall cladding, exterior paint, roof and spouting condition) were also associated with mould in the whole house, with each of these factors associated with statistically significant increased odds of mould in at least one of the three surveys, except roof condition (Table 5). Analysis of aggregated domains showed a significant dose-response trend for climate zone, which was not observed for the other outcomes, with aORs for houses in the southern (colder) zone ranging from 0.2-0.5 (p<0.05 for 2010 and 2015, p=0.08 in 2005 for trend; Table 6). Other associations were similar, or in some cases more pronounced, to those described for mould in living and bedrooms. In particular, across all three surveys a significant positive dose-response trend was observed, with the number of occupants, with aORs ranging from 2.4-4.5 for five or more occupants compared to 1-2 occupants (Table 6).

3.4.3 Musty Odour

Tenancy and the presence of an open fireplace both increased the odds of musty odour in the 2010 survey (aOR 3.1, p<0.05 and aOR 7.6, p<0.001, respectively) but this was not shown in the 2015 survey (Table 3.3). Fibre-cement cladding type was consistently associated across both surveys, with a greater risk of musty odour (aOR 4.7 and 6.1, respectively; $p<0.05$), and a similar association was found for brick cladding, but this was observed only in the 2015 survey (aOR 14.3, $p<0.01$). However, confidence limits were wide as these cladding types were not common (Table 3.3). Of interest, presence of a kitchen range hood was associated with reduced odds of musty odour, but this was statistically significant only for the 2015 survey.

Associations with aggregate domain variables were generally similar to those observed for visible mould, with insulation, ventilation and envelope defects (BEC) showing significant dose-response trends (Table 4). Dose-response associations ($p<0.01$-0.001 for trend) were particularly consistent for building envelope defects (BEC) with aORs ranging from 4.3-15.9, $p<0.05$. Also, similar to findings for visible mould, strong and consistent associations were observed with inspectors’ overall condition ratings (OCR) (Table 3.4).

Table 3.5: Multivariate analysis of mould in the whole house in three House Condition Surveys

		2005		**2010**		**2015**
		N=536		N=486		N=542
		P=0.0000		P=0.0000		P=0.0000
		R^2 =0.34		R^2 =0.25		R^2 =0.27
	N	aOR	N	aOR	N	aOR
Age of house						
Pre 1930	*82*	*Ref*	*56*	*Ref*	*61*	*Ref*
1930-1979	*297*	2.3 (0.5, 8.4)	*242*	*0.9 (0.4, 2.0)*	*285*	0.6 (0.3, 1.2)
Post 1980	*157*	0.3 (0.0, 3.4)	*160*	0.8 (0.3, 2.1)	*196*	**0.4 (0.2, 1.0)****
Missing/mixed			*28*	1.5 (0.4, 4.9)		
Climate zone						
North	*291*	*Ref*	*159*	*Ref*	*177*	*Ref*
Mid	*104*	**0.2 (0.0, 0.7)***	*226*	1.3 (0.7, 2.5)	*153*	0.4 (0.1, 2.3)
South	*141*	**0.2 (0.1, 0.9)***	*101*	0.6 (0.3, 1.3)	*212*	**0.2 (0.0, 0.7)****
Occupants						
1 to 2	*267*	*Ref*	*272*	*Ref*	*326*	*Ref*
3 to 4	*208*	1.1 (0.4, 2.9)	*167*	**1.7 (1.0, 2.7)***	*167*	**1.9 (1.2, 3.2)****
5 or more	*61*	**4.0 (1.3, 11.7)****	*47*	**2.3 (1.1, 5.0)***	*49*	*2.2 (1.0, 5.1)^*
Tenure						
owner occupier	*536*		*378*	*ref*	*399*	*Ref*
tenant	*0*	*NA*	*108*	1.2 (0.7, 2.2)	*143*	0.9 (0.6, 1.6)
Range hood						
No	*324*	*Ref*	*194*	*Ref*	*202*	*Ref*
Yes	*212*	0.9 (0.4, 2.2)	*292*	0.9 (0.6, 1.5)	*340*	*0.7 (0.4, 1.1)^*
Bathroom ventilation						
None	*381*	*Ref*	*249*	*Ref*	*249*	*Ref*
Vented to outside	*155*	0.8 (0.3, 2.7)	*194*	**0.4 (0.3, 0.7)*****	*266*	**0.6 (0.4, 1.0)***
missing			*43*	0.8 (0.4, 1.8)	*27*	0.5 (0.2, 1.6)
Sufficient subfloor ventilation						
Yes	*154*	*Ref*	*74*	*Ref*	*97*	*Ref*
No	*254*	0.5 (0.2, 1.2)	*242*	1.6 (0.8, 3.4)	*224*	0.9 (0.5, 1.7)
Slab foundation	*128*	0.5 (0.1, 2.5)	*170*	1.4 (0.6, 3.0)	*145*	0.7 (0.3, 1.3)
Roof condition rating						
Excellent/Good	*396*	*Ref*	*287*	*Ref*	*294*	*Ref*
Moderate/poor	*140*	0.5 (0.2, 1.5)	*171*	1.4 (0.8, 2.3)	*230*	1.5 (0.9, 2.7)
Missing			*28*	1.2 (0.5, 3.2)	*18*	1.2 (0.3, 4.2)
Window condition						
Excellent/Good	*361*	*Ref*	*249*	*Ref*	*303*	*Ref*
Moderate/poor	*175*	**6.4 (2.2, 18.2)*****	*223*	1.2 (0.7, 2.0)	*239*	1.6 (0.9, 2.9)
Missing			*14*	**0.2 (0.1, 1.0)***		
Wall cladding paint deterioration						
No	*266*	*Ref*	*366*	*Ref*	*379*	*Ref*
Yes	*270*	1.2 (0.5, 3.2)	*120*	1.0 (0.6, 1.8)	*163*	**2.3 (1.3, 3.9)*****
Wall cladding condition						
Excellent/Good	*390*	*Ref*	*128*	*Ref*	*315*	*Ref*
Moderate/poor	*146*	*2.5 (1.0, 6.6)^*	*339*	**2.3 (1.3, 4.2)****	*227*	1.1 (0.6, 2.0)
Missing			*19*	*3.2 (0.9, 10.8)^*		
Cladding type						
Timber weatherboards	*178*	*Ref*	*94*	*Ref*	*123*	*Ref*
Fibrecement	*52*	1.5 (0.3, 7.9)	*43*	1.5 (0.6, 4.0)	*72*	1.7 (0.7, 4.0)
Brick	*82*	2.5 (0.6, 11.3)	*59*	1.2 (0.5, 3.0)	*107*	1.6 (0.7, 3.7)
Mixed/other	*224*	1.3 (0.5, 3.8)	*290*	0.7 (0.3, 1.3)	*240*	*1.9 (1.0, 3.5)^*
Spouting condition						
Excellent/good	*428*	*Ref*	*307*	*Ref*	*339*	*Ref*
Moderate/poor	*108*	**3.3 (1.2, 8.8)***	*143*	*1.7 (1.0, 2.9)^*	*201*	1.3 (0.7, 2.5)
Missing			*36*	1.0 (0.4, 2.6)	*2*	0.4 (0.0, 17.3)

Note: ^p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001; NA data not available. All models adjusted for surveyor (except 2005 because of collinearity with zone), 30-day rain (mm), 30-day mean high temperature (°C), age of house, shade, close to a busy road, gas heaters, wall insulation, ceiling insulation, roof material, window material, double glazing, ponding or leaks under house & missing or leaky flashings.

Table 3.6: Aggregated multivariate analysis of mould in the whole house in three House Condition Surveys

		2005		2010		2015
		N=526		N=480		N=527
		P=0.0000		P=0.0000		P=0.0000
		R^2 =0.26		R^2 =0.21		R^2 =23
	N	aOR	*N*	aOR	*N*	aOR
Climate zone						
North	*286*	*Ref*	*158*	*Ref*	*171*	*Ref*
Mid	*97*	**0.2 (0.1, 0.8)***	*222*	0.9 (0.5, 1.7)	*147*	0.6 (0.1, 3.4)
South	*143*	0.5 (0.2, 1.4)	*100*	**0.4 (0.2, 0.9)***	*209*	**0.2 (0.1, 0.8)***
trend		P=0.08		P<0.05		P<0.05
Occupants						
1 to 2	*266*	*Ref*	*271*	*Ref*	*315*	*Ref*
3 to 4	*201*	1.3 (0.6, 3.1)	*162*	**1.8 (1.1, 2.9)***	*164*	**2.0 (1.2, 3.1)****
5 or more	*59*	**4.5 (1.6, 12.4)*****	*47*	**3.0 (1.4, 6.5)****	*48*	**2.4 (1.1, 5.0)***
trend		P<0.01		P<0.01		P<0.01
Tenure						
owner occupier	*529*		*372*	*Ref*	*385*	*Ref*
tenant	*0*	-	*108*	1.2 (0.7, 2.1)	*142*	1.2 (0.8, 2.0)
Ventilation/3 (kitchen/bathroom/clothes dryer)						
0	*234*	*Ref*	*142*	*Ref*	*132*	*Ref*
1	*181*	1.5 (0.6, 3.4)	*166*	**0.5 (0.3, 0.8)****	*172*	0.9 (0.5, 1.6)
2	*111*	0.5 (0.1, 1.9)	*139*	**0.3 (0.2, 0.6)*****	*190*	**0.4 (0.2, 0.7)*****
3		§	*33*	**0.1 (0.0, 0.3)*****	*33*	**0.3 (0.1, 0.7)****
trend		NS		P<0.001		P<0.001
Insulation/3 (ceiling/underfloor/wall cavity)						
3	*199*	*Ref*	*144*	*Ref*	*118*	*Ref*
2	*143*	2.3 (0.7, 7.4)	*185*	1.0 (0.6, 1.7)	*311*	1.5 (0.8, 2.7)
1	*157*	**4.4 (1.3, 14.9)***	*151*	1.2 (0.6, 2.1)	*90*	**3.8 (1.7, 8.6)*****
No insulation	*27*	**5.8 (1.1, 30.4)***			*8*	*5.9 (0.8, 42.5)^*
trend		P=0.01		NS		P<0.001
Subfloor/3 (ponding or leaks/absence of ground cover/insufficient ventilation)						
0	*176*	*Ref*	*27*	*Ref*	*210*	*Ref*
1	*179*	0.7 (0.3, 2.1)	*382*	*2.2 (0.9, 5.6)^*	*140*	1.1 (0.6, 1.9)
2	*151*	0.4 (0.1, 1.3)	*71*	**4.1 (1.3, 12.5)****	*154*	1.5 (0.9, 2.6)
3	*20*	0.4 (0.1, 3.0)			*23*	1.2 (0.4, 3.8)
trend		NS		P=0.01		NS
BEC/5 (Moderate to serious condition of; roof cladding/wall cladding/windows/exterior paint/spouting and guttering)						
0-1	*303*	*Ref*	*155*	*Ref*	*236*	*Ref*
2-3	*165*	**3.7 (1.4, 9.4)****	*159*	*1.6 (0.9, 2.8)^*	*137*	**2.1 (1.2, 3.7)****
4-5	*58*	**15.2 (5.2, 44.7)*****	*82*	**5.8 (2.7, 12.5)*****	*154*	**3.0 (1.6, 5.8)*****
Missing			*84*	1.2 (0.6, 2.2)		
trend		P<0.001		P<0.001		p<0.001
Overall Condition Rating (OCR)						
Excellent	*254*	*Ref*	*123*	*Ref*	*237*	*Ref*
Moderate	*184*	**5.0 (1.3, 19.1)***	*125*	**2.5 (1.4, 4.7)****	*218*	**3.6 (2.2, 6.0)*****
Poor	*88*	**26.8 (7.0, 102.3)*****	*108*	**9.3 (4.3, 20.2)*****	*95*	**11.1 (5.2, 23.5)*****
Missing			*124*	1.5 (0.8, 3.0)		
trend		P<0.001		P<0.05		P<0.001

Note: All models adjusted for surveyor (except 2005 because of collinearity with zone), 30-day rain (mm), 30-day mean high temperature (°C). § perfectly explains failure; ^p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001; - data not available; NS not significant.

3.5 Discussion

This study showed that a wide range of house characteristics were independently associated with indoor visible mould and musty odour, including tenure, occupancy, climate, ventilation, insulation and building envelope condition, with evidence of dose-response associations across multiple surveys.

3.5.1 Visible mould

Compared to 2005, reporting of visible mould increased substantially in the 2010 and 2015 surveys, from 4% to 15% and 18% of surveyed homes. This may be due to methodological differences, with the two later surveys including rental homes and introducing assessor training. In addition, the vast majority of assessments for the 2005 survey were conducted in summer (the driest months in New Zealand), whereas assessments conducted for the 2010 and 2015 surveys were also conducted in the colder and wetter seasons i.e., winter and spring.

Poor condition of the building envelope was strongly associated, in a dose-dependent fashion, with increased visible mould, both when using the building envelope condition index (BEC) created for this analysis, and the building inspectors' OCR. The OCR was consistently more strongly associated with both visible mould and musty odour than our BEC. However, since visible mould was one of the condition factors contributing to the OCR this is to be expected. The few other studies that have assessed associations between poorer building condition either assessed by self-report [15, 22] or by building assessor [24] found a similar relationship. Unlike previous studies, our study assessed specific condition defects that may underpin this association, demonstrating that roof and wall claddings as well as windows, spouting and exterior paint all contribute to the buildings’ waterproofing.

Extract ventilation (particularly bathroom ventilation) was associated with reduced living and bedroom mould, with clear dose-response associations observed when ventilation data were aggregated, with more types of ventilation (kitchen, bathroom and clothes dryer) associated with reduced likelihood of visible mould. One other study also showed reduced self-reported visible mould in homes that used kitchen range hoods [14], whereas another study reported the opposite, with kitchen and bathroom extract ventilation associated with an increase in mould [17].

Although individual insulation factors were not significantly associated with mould in the initial multivariate analysis, when aggregated, there was evidence of a dose-response association. This is consistent with an earlier phone survey conducted in New Zealand, that found that a lack of any insulation was associated with increased visible mould [15], and a study from the UK that found that houses with less than 250mm loft insulation had an increased risk of indoor mould [17]. Two studies assessing the results of insulation interventions also found reduced visible mould [12, 19]. The heating behaviour of the occupants is likely to impact these associations, but in the one survey where this information was available (2015), it was not found to significantly change these findings (data not shown). Also, type of heating present (electric/gas-flued/gas-unflued/enclosed fire/open fire/central heating) was analysed for all three surveys, but none of these types of heaters met the criteria for inclusion in the multivariate models presented here (i.e. they were not significantly associated across at least two surveys in univariate analysis - see methods), except presence of an open fireplace. In contrast to our findings, some studies have shown that energy-efficiency interventions (including insulation retrofits) may enhance the presence of some indoor fungi [31]. This is likely due to reduced air-exchange [32, 33] in houses that are already reasonably airtight, unlike most houses in New Zealand which are generally fairly draughty.

Consistent with other studies [15, 17, 19, 34], rental tenure and, number of occupants, were associated with indoor mould. Associations with rental tenure cannot be explained by BEC, insulation and ventilation as analyses were controlled for these factors. However, as shown previously using the same survey data [25, 27], rental homes are more likely to have higher occupant density, which may contribute to the higher risk of indoor mould as demonstrated in other studies for both visible mould [17] and airborne fungi [35]. Information for floor area was available for 2005 and 2010, and a ratio of occupants to floor area was calculated for these two surveys. This ratio was significantly associated with mould in the whole house, and to a lesser degree mould in living and bedrooms, but not musty odour (data not shown). However, the explained variance of this variable (R^2=0.001) was not greater than that of the number of occupants only, and therefore, for consistency, we instead used the number of occupants in all multivariate models.

3.5.2 Musty Odour

No association between number of occupants and musty odour was found, but musty odour was associated with rental tenure. To our knowledge, no other studies have reported associations with occupancy and tenancy and musty odour, although studies assessing the health impact of mouldy odours frequently adjust for occupant density, as it is considered a confounding factor for asthma and allergy [6, 36].

While there were several similarities between associations with mould and musty odour, there were also some differences, and the correlation between both variables was relatively poor ($r=0.14$, $p<0.01$ in 2010 and $r=0.23$, $p<0.001$ in 2015). The similarities were more apparent when variables were aggregated; for example, similar effects and trends were demonstrated for tenure, aggregated ventilation, insulation and building envelope condition. However, there were important differences between characteristics predicting visible mould and musty odour in the analysis of individual characteristics. For example, the presence of an open fire was associated with musty odour and not mould. The reason is not clear, but open fires may indicate an older house that has not been renovated, as open fires have not been commonly installed in new houses built after circa 1940. Also, open chimneys (a common feature of open fires) may result in musty odour either due to ingress of moisture, an uncontrolled open vent, or increased draughtiness. Another characteristic associated with musty odour, but not visible mould, was cladding type. Fibre cement wall cladding was associated with musty odour in both surveys for which data was available, while brick cladding was associated with musty odour in 2015 only. Fibre cement cladding may have characteristics that increase risk of moisture ingress [37] but associations with musty odour (or mould) have not previously been reported, so results should be interpreted with caution, particularly since analyses were based on a relatively small number of houses with this cladding type. Brick cladding is often considered low maintenance, but periodic repointing is required, but often not done, which may result in excess moisture entering the wall cavity.

3.5.3 Strengths and weaknesses.

A strength of the study is the level of detail of the data collected on physical aspects of the houses involved, along with measures of mould that do not rely on home occupants' self-reports, which may be biased. On the other hand, musty odour assessed by inspectors may be less accurate than self-reported odour, as it may be transient and therefore a single assessment by an inspector may increase rather than decrease exposure measurement error. Another weakness is that musty odour assessment is subjective and not easily standardised across inspectors. As our samples did not include any apartments and the vast majority involved timber framed houses, it is unclear whether results are generalisable to non-timber framed houses, although several findings (e.g., for insulation, extraction fans and "poor repair") were comparable with previous studies that included non-timber-framed buildings [14, 17, 18, 19, 24].

The explained variance (R^2) of the regression models described in Tables 3-6 was relatively low (18 – 43%), indicating a large proportion of unexplained variance. The lack of data included in these surveys on human behaviour, in particular the use of heating and ventilation is an important weakness, which if included, would likely explain more of the variance in indoor mould and musty odour. Other important considerations for such surveys are to include both number of occupants and floor area, so accurate ratios of persons to area can be determined. Information on age-ranges and household habitual behaviours, e.g., proportion of time spent at home, may also improve the ability of future studies to explain visible mould and musty odour. The relatively low proportion of houses in each of the three samples with mould and musty odours (4-18%) has resulted in reduced power to identify associations, particularly for house characteristics and conditions that are relatively rare. Although this was partially mitigated by analysing and comparing results across three surveys, future surveys likely require larger sample sizes to ensure sufficient power for all potential associations to be validly assessed. Also, avoiding sampling during summer (the driest months in New Zealand) may increase the proportion of homes where mould and musty odour are detected.

3.6 Conclusions

In conclusion, this study showed the importance of building envelope condition in avoiding harmful damp-related exposures. It also identified several other modifiable risk factors that may contribute to the development of effective interventions to reduce indoor dampness and mould. In particular, mechanical extract ventilation in kitchens and bathrooms, along with regular maintenance of the building envelope, with attention to spouting, wall and window condition may be important in protecting homes from indoor mould and musty odours.

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Name of candidate:	Phoebe Taptiklis
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GRS Version 5 – 13 December 2019
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4 Associations of house characteristics with indoor dampness and measured moisture: results from three New Zealand House Condition Surveys in 2005, 2010 and 2015.

Phoebe Taptiklis, Robyn Phipps, Mark Jones, Jeroen Douwes

Published in: ***Building and Environment 208.*** **10.1016/j.buildenv.2021.108508 (2022)**

4.1 Abstract

Associations between house characteristics and inspector-assessed subjective indoor dampness (yes/no) and measured floor and ceiling joist timber moisture were measured, using the 2005, 2010 and 2015 New Zealand House Condition Surveys, involving 1572 timber-framed houses. We conducted logistic (dampness) and linear regression (moisture) for each survey separately and mutually adjusted for other house characteristics (ventilation, insulation, subfloor defects, building envelope condition (BEC) defects, tenure, number of occupants), climate zone (latitude), rainfall and outdoor temperature. The odds of subjective damp increased with: more BEC defects (p for trend <0.001), with adjusted odds ratios (aORs) of 3.9-9.6 (p<0.001) across surveys for houses with 4 or 5 (of 5) defects, compared with houses with ≤1 defect; more subfloor defects

(p for trend <0.01 for 2010 and 2015 surveys); less ventilation (p for trend <0.05 for 2010 and 2015 surveys); less insulation (p for trend ≤0.05 for 2010); and increased occupancy (aORs 1.2-2.3, for ≥5 occupants compared to 1-2, not significant). Dampness was more common in rental houses (aORs 1.6 to 2.2, p<0.05 in 2015). Floor joist moisture content was higher in houses with more subfloor (1.2%-1.9% increase per defect, p for trend ≤0.01) and BEC defects (1.5%-1.8% for houses with 4-5 defects, p<0.001 for 2005 and 2015 surveys). In conclusion, subfloor and building envelope defects were associated with both inspector-assessed dampness and objectively measured moisture in floor joists. Less insulation, ventilation and higher occupancy were associated with increased subjective dampness but not with measured moisture.

4.2 Introduction

Consistent associations between indoor dampness and respiratory ill health have been reported [1, 2], with mould exposure hypothesised to play an important role, although the evidence for this has been equivocal [3-6]. While much attention has gone into improving quantitative measures of indoor mould [7, 8], the strongest associations with ill health are generally observed with qualitative observations of dampness and mouldy odour, and semi-quantitative observations of mould (as measured by extent or size of mould contaminating on wall and other surfaces) [1, 9, 10].

House and household characteristics have been associated with subjective dampness indicators in several studies, including higher occupancy [11-14], tenancy vs home ownership [15-17], no or poor insulation [18, 19], lack of (mechanical) ventilation [15, 16, 20], older houses [11, 16, 20-22], and poor repairs and maintenance [16, 23, 24]. Some of these characteristics have also been associated with higher indoor relative humidity or other objective measures of dampness, including higher occupancy [25, 27, 28], lack of insulation [19, 27], lack of efficient and effective heating [25, 27, 29] and less ventilation [30]. However, results have not always been consistent, potentially because currently there are no standardised and widely accepted indicators of, or validated methods for, measuring indoor dampness. Similarly, reported associations between home characteristics and indoor mould have been equivocal [31, 32], likely due to different approaches used to measure mould. Also, most studies have focused on only a small number of house characteristics, resulting in significant knowledge gaps. In particular, although improved house maintenance is frequently referred to in advice for occupants to reduce indoor dampness [33], and epidemiological studies have identified “poor repair” and “infrequent maintenance” as risk factors for indoor dampness and mould, [16, 23], it remains unclear which specific aspects of maintenance are most critical. Improved understanding of the specific house and household characteristics that contribute to indoor dampness will facilitate the development of more effective interventions.

We have previously reported associations between house characteristics and visible mould and musty odour using data from three iterations of the New Zealand House Condition Survey, conducted in 2005 (n=565), 2010 (n=491) and 2015 (n=560) [21]. These three surveys collected detailed data on the physical characteristics of these houses as well as some household characteristics, and showed that poorer ventilation, insulation and condition of the building envelope were independently associated with increased visible mould and musty odour (both inspector assessed), after adjustment for climate and other household characteristics including tenure and number of occupants [23]. The aims of the current study were to assess associations with outcomes of inspector-rated subjective (feeling of) indoor dampness and moisture measurements (moisture content) taken from ceiling and floor joist timbers using data from the same three surveys, with the overall goal of improving understanding of the determinants of indoor dampness, thus contributing to improved interventions to reduce indoor dampness.

4.3 Methods

The New Zealand House Condition Survey (HCS) is conducted by the Building Research Association of New Zealand (BRANZ) and has been undertaken approximately every five years since 1994 [28]. The study reported here, used data collected from the three most recent surveys i.e. 2005, 2010 and 2015. The sampling methodology and assessor training are described in detail elsewhere [35-37] and [37] respectively. Briefly, the three surveys were predominantly restricted to single family, timber-framed dwellings. Apartments were not included, as they were an uncommon housing typology in New Zealand during the period of the three HCS. While using almost identical assessment protocols, there were some differences between the three HCSs: in 2005, the sample was limited to only owner-occupied houses in the three largest New Zealand cities and outlying regions (Auckland and Wellington in the North Island, and Christchurch in the South Island); and for the 2010 and 2015 HCSs, rental houses and houses located in other cities and rural towns were included, and a sampling structure was developed to capture a more representative sample of dwellings. The sampling structure for the 2010 and 2015 surveys involved dividing the country into 13 strata, 11 of which corresponded to urban areas, with the remaining two strata involving the rest of the North Island, and the rest of the South Island. Cluster-sampling was used within strata based on census mesh-blocks (smallest statistical area unit). Also, from 2010 onwards, additional training for the home inspectors was provided to increase the consistency of damp and condition assessments. This involved a day of theoretical training, including how to conduct moisture assessments, followed by supervised inspections. Weathertightness, a term used in New Zealand to describe a building's ability to prevent water from penetrating the building envelope [38] was not a specific category assessed by the surveys.

4.3.1 Climatic conditions and housing stock in New Zealand

New Zealand has a temperate maritime climate, characterised by relatively high year-round humidity and a relatively small annual range (10 ^{o}C) of mean daily temperature. Its housing stock consists predominantly of timber construction. The sample of houses included in the three housing condition surveys described in this paper is generally reflective of the range of residential construction styles found in New Zealand, although since 2015 a consistently higher proportion of multi-unit, multi-level residential buildings have been constructed, and these are not well represented in the samples used here, which are predominantly stand-alone, single-family dwellings.

4.3.2 House characteristics

The surveys included >1500 individual components, including the presence of insulation, heaters and ventilation systems, site details such as location, slope of site, and exposure to noise, air pollution and sun. Other information collected included number of occupants, year of construction and date of survey. For the current study, 77 variables were selected as plausibly associated with indoor or framing moisture (Table 4.2). Inspection of wall cavities to assess the presence of insulation were conducted in the 2005 survey, but this was discontinued in later surveys due to practicality and health and safety concerns. In these cases, wall insulation was identified based on the house age (in relation to changes in building code insulation requirements) and conversations with the occupants.

Information on ceiling insulation was available in two dimensions i.e. proportion of the ceiling (of the whole house) covered, and thickness of the insulation. These variables were analysed separately in univariate analysis, which showed that an index combing the two dimensions improved the explained variance (in univariate analysis) compared to either variable separately. Therefore, in multivariate analysis ceiling insulation was analysed using an index describing both thickness and coverage (least/mid/most). For the ceiling insulation index we allocated one point to insulation that was <50mm thick, 2 points for insulation thickness of 50-100mm and 3 points if thickness was >100mm. For the proportion of the ceiling covered we allocated 1 point for 0-25% coverage, 2 points for 30-75% coverage, and 3 points for 80-100% coverage. The values for these variables were subsequently summed and then reduced to a 3-point scale using the following cut-points: 1-3= "Least"; 4-5= "Mid"; and 6= "Most". The cut-points were chosen to balance the need to reflect real differences in insulation between sub-groups, whilst ensuring sufficient observations in each sub-group to conduct multivariate regression analyses with adequate power.

Along with detailed recording of material types for most of the building components, condition ratings on a 5-point scale (Excellent, Good, Moderate, Poor, Serious) were used for major components i.e., windows, doors, roof, gutters, subfloor ventilation, exterior paint condition, etc. These rating values were based on inspectors' assessments of the urgency and level of any potential repair required to bring the component to "as new" condition, with "as new" defined as "no signs of damage/wear and tear, and no maintenance requirements at present. For this study, rating variables were used as a binary measure: excellent/good versus moderate/poor/serious. The primary reason for grouping the results this way was to ensure sufficient frequencies in each (sub-) group.

4.3.3 Subjective indoor dampness

Dampness was assessed (subjectively) by inspectors after completing the indoor inspection using the following categories: dry, some damp, damp throughout [33]. These categories were based on a subjective "feeling" of dampness. For the analyses described in this paper, "some damp" and "damp throughout" were combined and used in a binary dry/damp variable. The 2010 survey included a high number of missing values for the dampness variable (29%), particularly for the earliest period of data collection. Comparing houses with and without missing data for dampness showed that key home characteristics (i.e. house age, presence of insulation, presence of mechanical ventilation, number or type of heaters and visible mould) did not appreciably differ between both groups (data not shown), suggesting that missing data is unlikely to have resulted in a systematic bias of our sample. Results reported in the tables are based on houses with no missing data for the main outcome variables (i.e. subjective dampness and measured moisture in ceiling and floor joists).

4.3.4 Moisture measurements

Percentage moisture content (%MC) was measured using a two-pronged electrical resistance meter (Protimeter CEM DT-125) in the timber structural framing of houses where access to roof space or subfloor allowed. Protimeters were chosen because they are a standard instrument used in the construction industry in New Zealand and were found to be “potentially useful” in a 2018 review of the literature [39]. The instruments were calibrated once at the start of each study.

In the ceiling joists, a single measurement was taken. In the floor joists, two measurements were taken from different joists at least 1.5m apart, the results of which were averaged for subsequent analyses. The instruments were calibrated at the start of each study. They were not re-calibrated and repeatability testing was not conducted.

4.3.5 Climate data

For each house, we obtained twenty-four-hour rainfall and daily maximum temperatures for a 30-day period prior to the date of the survey. Data was sourced from the National Climate database [40] from the weather station closest to the house (generally within <10 km). Data were expressed as 30-day total rainfall (mm) and mean 30 daily maximum temperature (^{o}C).

4.3.6 Data analyses

Analyses were conducted for each HCS separately using STATA 15 (StataCorp LP, TX, USA). Associations between home characteristics and subjective damp were assessed using logistic regression adjusting for other co-variates. House characteristic variables tested are listed in table 2. As there were a large number of home characteristics that could potentially be associated with indicators of home dampness, we initially conducted univariate (or unadjusted analyses) for each of these variables. We subsequently conducted multivariable regression analyses (mutually adjusting for other potential confounders). For these analyses we only included variables that met one of two requirements: 1) in unadjusted analyses, associations were consistent and borderline statistically significant ($p \leq 0.1$) for that variable in two or more of the surveys; or 2) consistent associations with damp were observed across all three surveys, and statistically significant ($p \leq 0.05$) in at least one. This approach was used to reduce the number of variables in these models, thus increasing statistical power and reducing risk of multicollinearity. In the results section we describe only the fully adjusted analyses based on these multivariable models. For measured moisture, linear regression was used following the same approach. All models were further adjusted for surveyor, by including surveyor ID as an independent categorical variable (except 2005, as the surveyor who undertook the house assessment was highly correlated with the variable for climate zone, thus resulting in multi-collinearity), average 30-day rain (mm) and 30-day average maximum temperature (oC). A flow chart visualising the analysis process has been included in the supplementary materials (Appendix 1).

In addition to considering individual house characteristics, we also conducted analyses involving aggregated variables by combining variables within the same domains. Prior to doing so, we checked for consistency of associations (negative or positive) for each individual variable. The aggregated variable for mechanical ventilation involved combining information on independently operated kitchen, bathroom and clothes dryer external ducting into one variable (with each fan/duct controlling a particular moisture point source). For this purpose, we used a score of “1” for the presence, and “0” for the absence of each of these ventilation types, and this was summed for each house and subsequently used in the analysis (the total sum variable ranged from zero to three). For the insulation domain, the presence of roof, underfloor and wall cavity insulation (using the assumptions described above under “House characteristics” for wall insulation) were summed, resulting in a score ranging from zero (no insulation) to three (all three areas insulated). The subfloor domain summed the presence of ponding or leaks, insufficient subfloor ventilation, and lack of ground moisture barrier, again resulting in a combined score ranging from zero to three. The building envelope condition (BEC) domain summed moderate to serious condition of; roof cladding, wall cladding, exterior paint, windows and spouting/guttering, with a combined score ranging from zero to five. These aggregate domains allowed dose-response associations within each domain to be assessed. In the analysis, houses with a score of three were used as the reference category for the insulation domain, due to low numbers in the category with zero insulation. For all other aggregate variables, the houses with a combined score of zero were used as the reference category. Details about how variables were categorised and aggregated for inclusion in both multivariate and analysis within domains are presented in Appendix 2

In addition to measuring associations using the BEC domain as described above, we also conducted analyses using the overall condition rating (OCR) provided by the assessors at the end of the survey as a single summary condition rating for the house rated on a 3-point scale: well maintained, moderately maintained or poorly maintained. This was based on the assessors’ judgement of all maintenance needed anywhere in the house, to bring it to “as new” standard. Materials and fittings, both inside and out, were included in the assessment, and the presence of mould was considered a condition in need of maintenance.

Tests for trend were conducted by converting each summed categorical domain to a continuous variable in regression analyses and using the resultant p-value. Collinearity was tested for all models using variance inflation factors, and all scores were under three.

4.4 Results

The three HCSs differed with regards to the season in which they were conducted i.e. in 2010 the majority of houses were assessed in the colder and wetter months of winter and spring, whereas the 2005 survey was conducted almost entirely in summer (Table 4.1). The age distribution of the houses across the three surveys was similar, with around half built between 1930-1979, a third built after 1979, and 11%-15% built before 1930. Houses in the 2010 and 2015 surveys, which included rental properties (22% and 27%, respectively), were more likely to have fewer bedrooms and occupants (Table 4.1). The 2010 survey included a lower proportion of well-maintained houses (25%) compared to the 2005 (50%) and 2015 (44%) surveys.

Subjective dampness was reported most frequently in 2010 (26%), compared to 12% in 2005, and 15% in 2015. Roof moisture and 30-day rainfall was also highest in 2010 (Table 1). In contrast, floor joist moisture was highest in the 2005 survey (19.2% moisture content (MC)) compared to approximately 16.5% MC for the two later surveys. Histograms demonstrating the range of moisture measurements are presented in Figure 4.1.

Table 4.1: Sample Characteristics

	2005 (565 houses)	*2010 (491 houses)*	*2015 (560 houses)*
	Mean ± SD	Mean ± SD	Mean ± SD
Roof joist moisture (MC)	10.8 ± 1.7	11.9 ± 3.3	10.6 ± 5.1
Floor joist moisture (MC)	19.2 ± 4.4	16.5 ± 2.7	16.6 ± 3.4
Assessed for moisture/damp	*N*(%)	*N*(%)	*N*(%)
Floor joist moisture	326 (58)	286 (58)	323 (58)
Roof joist moisture	482 (85)	376 (77)	422 (75)
Subjective dampness	565 (100)	348 (71)	539 (96)
Subjective damp			
Of assessed: Dry	502 (88)	257 (74)	459 (85)
A little damp	54 (10)	50 (14)	53 (10)
Damp throughout	9 (2)	41 (12)	27 (5)
Survey season			
Summer (December-February)	540 (96)	50 (10)	172 (31)
Autumn (March-May)	10 (2)	-	149 (27)
Winter (June-August)	-	56 (12)	1 (0)
Spring (September-November)	15 (3)	383 (78)	238 (43)
30-day rain			
0-50mm	302 (53)	206 (42)	308 (56)
51-100mm	212 (38)	104 (21)	199 (36)
101-150mm	44 (8)	70 (14)	41 (7)
151mm or more	7 (1)	107 (22)	6 (1)
30-day temp (average)			
<15°C	0	177 (36)	48 (9)
15.1-20°C	183 (32)	260 (53)	233 (42)
20.1-25°C	315 (56)	49 (10)	229 (41)
>25°C	67 (12)	1 (0.2)	47 (8)
Climate zone			
North	304 (54)	161 (33)	183 (33)
Mid	111 (20)	227 (46)	159 (28)
South	150 (26)	101 (21)	218 (39)
Age category			
Pre 1930	87 (15)	58 (13)	62 (11)
1930-1979	307 (55)	242 (52)	294 (53)
1980 and older	167 (30)	163 (35)	204 (36)
Overall Condition Rating (OCR)			
Well maintained	280 (50)	125 (25)	243 (44)
Reasonably maintained	195 (35)	127 (26)	220 (39)
Poorly maintained	85 (15)	112 (23)	96 (17)
Missing	5 (1)	127 (26)	
Tenure			
Rented	-	108 (22)	149 (27)
Owner occupied	565 (100)	383 (78)	411 (73)
Occupants			
1 to 2	273 (48)	277 (56)	336 (60)
3 to 4	213 (38)	167 (34)	175 (31)
5 or more	63 (11)	47 (10)	49 (9)
Missing	16 (3)		
Bedrooms			
1 to 2	35 (6)	74 (15)	104 (19)
3 to 4	489 (87)	392 (80)	422 (75)
5 or more	41 (7)	23 (5)	32 (5.5)
Missing			2 (0.5)
Foundation Type			
Piles	321 (57)	314 (64)	339 (60)
Concrete slab	148 (26)	137 (28)	207 (37)
Mixed foundations	96 (17)	40 (8)	14 (3)
Cladding Type			
Timber weatherboard	186 (33)	97 (20)	128 (23)

Fibre cement	55 (10)	43 (9)	66 (12)
Brick	86 (15)	61 (12)	110 (20)
Mixed/other	238 (42)	290 (59)	256 (46)
Roof Type			
Metal roof	372 (66)	287 (58)	409 (73)
Concrete/clay tiles	183 (32)	201 (41)	121 (22)
Other	10 (2)	3 (1)	30 (5)

4.4.1 Subjective dampness

The presence of a rangehood, or extract ventilation over the cooker, was associated with less dampness in the 2010 and 2015 surveys (aORs 0.5 and 0.3, $p<0.05$; Table 4.2), but no association was found in the 2005 survey. Houses with the least ceiling space insulation (an index combining thickness and proportion of the ceiling covered) had a greater risk of dampness, statistically significant for the 2005 (aOR 3.1, $p<0.05$) and 2015 surveys (aOR 4.7, $p<0.05$). Additional analyses adjusting for the cumulative presence of ceiling insulation defects (gaps, settling, poor fit and general damage) did not appreciably change these results (data not shown). Ponding or leaks in the subfloor space were associated with increased indoor dampness, but this reached statistical significance only in the 2010 survey (aOR 2.1 to 2.6, $p<0.05$ in 2010 only). Poor window condition was also associated with more dampness (aORs 2.0 to 4.8), statistically significant ($p<0.001$) in the 2015 survey, and borderline statistically significant ($p<0.1$) in the other two surveys. Fibre-cement cladding was associated with significantly increased odds of indoor dampness (aORs 2.3 to 6.3; Table 4.2) and this was statistically significant ($p<0.05$) in both the 2005 and 2010 surveys (Table 4.2).

Table 4.2. Multiple regression analysis of subjective dampness in 3 House Condition Surveys.

			2005			**2010**			**2015**
			N=565/n=63			N=346/n=91			N=520/n=78
			P=0.0003			P<0.0000			P<0.0000
			R^2=0.14			R^2=0.31			R^2=0.41
	N	*n*	aOR (95% CI)	*N*	*n*	aOR (95% CI)	*N*	*n*	aOR (95% CI)
Occupants									
1 to 2	*273*	*21*	*Ref*	*202*	*45*	*Ref*	*315*	*50*	*Ref*
3 to 4	*213*	*31*	**2.2 (1.2, 4.2)****	*117*	*38*	1.3 (0.7, 2.5)	*159*	*16*	**0.4 (0.2, 0.9)***
5 or more	*63*	*10*	1.7 (0.7, 4.2)	*27*	*8*	1.2 (0.4, 4.0)	*46*	*12*	*2.3 (0.8, 7.0)^*
missing	*16*	*1*	0.9 (0.1, 7.8)						
Tenure									
Owner occupied				*272*	*67*	*Ref*	*386*	*46*	*Ref*
Rented			NA	*74*	*24*	1.6 (0.7, 3.6)	*134*	*32*	**2.2 (1.0, 4.8)***
Range hood									
No	*342*	*42*	*Ref*	*136*	*50*	*Ref*	*191*	*52*	*Ref*
Vented to outside	*223*	*21*	1.1 (0.6, 2.1)	*210*	*41*	**0.5 (0.2, 1.0)***	*329*	*26*	**0.3 (0.1, 0.6)*****
Bathroom ventilation									
None	*312*	*38*	*Ref*	*178*	*57*	*Ref*	*202*	*41*	*Ref*
Vented to outside	*164*	*14*	0.9 (0.4, 1.9)	*145*	*30*	1.2 (0.6, 2.4)	*258*	*27*	0.7 (0.3, 1.4)
Vented to roof space	*89*	*11*	1.1 (0.5, 2.6)	*23*	*4*	1.2 (0.3, 4.7)	*34*	*6*	0.9 (0.3, 3.4)
missing							*26*	*4*	0.8 (0.2, 4.5)
Wall insulation									
No	*326*	*46*	*Ref*	*228*	*73*	*Ref*	*125*	*29*	*Ref*
Yes	*239*	*17*	0.9 (0.5, 2.0)	*118*	*18*	0.5 (0.2, 1.3)	*135*	*12*	1.0 (0.3, 2.9)
missing							*260*	*37*	0.6 (0.3, 1.6)
Ceiling insulation									
Most	*421*	*35*	*Ref*	*203*	*52*	*Ref*	*213*	*30*	*Ref*
Mid	*101*	*18*	**2.4 (1.2, 4.8)****	*75*	*18*	0.7 (0.3, 1.6)	*214*	*28*	1.4 (0.6, 3.0)
Least	*43*	*10*	**3.1 (1.3, 7.8)****	*11*	*4*	1.4 (0.3, 6.9)	*25*	*10*	**4.2 (1.3, 13.9)***
Missing				*57*	*17*	1.5 (0.6, 3.8)	*68*	*10*	0.8 (0.3, 2.4)
Subfloor ventilation sufficient									
Yes	*162*	*25*	*Ref*	*46*	*12*	*Ref*	*94*	*19*	*Ref*
No	*267*	*32*	0.7 (0.4, 1.3)	*182*	*62*	1.6 (0.6, 4.5)	*212*	*45*	1.3 (0.5, 3.1)
Slab foundation	*136*	*6*	*0.4 (0.2, 1.2)*	*120*	*17*	1.3 (0.4, 4.14)	*214*	*14*	0.4 (0.1, 1.2)
Missing									
Ponding /leaks under house									
No	*528*	*56*	*Ref*	*285*	*62*	*Ref*	*462*	*57*	*Ref*
Yes	*37*	*7*	2.6 (0.7, 9.8)	*61*	*29*	**2.6 (1.1, 6.2)***	*58*	*21*	2.1 (0.7, 6.6)
Roof condition rating									
Excellent/Good	*414*	*39*	*Ref*	*200*	*33*	*Ref*	*286*	*28*	*Ref*
Moderate/poor/serious	*151*	*24*	1.2 (0.6, 2.2)	*126*	*51*	*1.8 (0.9, 3.5)^*	*216*	*49*	1.4 (0.6, 3.4)
Missing				*20*	*7*	2.3 (0.5, 10.2)	*18*	*1*	0.3 (0.3, 4.1)
Window condition									
Excellent/Good	*385*	*26*	*Ref*	*172*	*25*	*Ref*	*297*	*22*	*Ref*
Moderate/poor/serious	*180*	*37*	*2.0 (1.0, 4.0)^*	*164*	*67*	*2.1 (0.9, 4.9)^*	*223*	*56*	**3.9 (1.5, 10.1)****
Missing				*10*	*5*	2.1 (0.4, 12.6)			
Wall cladding paint deterioration									
No	*280*	*24*	*Ref*	*254*	*60*	*Ref*	*365*	*32*	*Ref*
Yes	*285*	*39*	1.3 (0.7, 2.3)	*92*	*31*	1.9 (0.8, 4.2)	*155*	*46*	**3.4 (1.5, 7.6)****
Wall cladding condition									
Excellent/Good	*414*	*31*	*Ref*	*81*	*17*	*Ref*	*307*	*28*	*Ref*
Moderate/poor/serious	*151*	*32*	*1.8 (0.9, 3.6)^*	*251*	*70*	0.6 (0.2, 1.5)	*214*	*50*	1.8 (0.8, 4.4)
Missing				*14*	*4*	1.1 (0.2, 6.5)			
Cladding type									
Timber weatherboards	*186*	*23*	*Ref*	*74*	*30*	*Ref*	*117*	*22*	*Ref*
Fibre-cement	*55*	*9*	**3.0 (1.1, 8.7)***	*28*	*11*	**6.2 (1.6, 23.9)****	*69*	*11*	2.0 (0.6, 6.7)
Brick	*86*	*7*	2.3 (0.8, 6.4)	*40*	*10*	0.9 (0.3, 3.1)	*104*	*7*	2.2 (0.6, 8.3)
Mixed/other	*238*	*24*	1.4 (0.7, 2.9)	*204*	*40*	1.1 (0.5, 2.3)	*231*	*38*	*2.4 (0.9, 5.9)^*
Spouting condition									
Excellent/good	*452*	*44*	*Ref*	*210*	*37*	*Ref*	*332*	*36*	*Ref*
Moderate/poor/serious	*113*	*19*	1.0 (0.5, 2.0)	*108*	*46*	**2.2 (1.1, 4.6)***	*188*	*42*	1.2 (0.5, 2.9)
Missing				*28*	*8*	1.3 (0.4, 4.7)			

N number in subgroup; n number in subgroup with dampness; ^p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001; NA data not available. All models adjusted for surveyor (except 2005 because of collinearity with zone), 30-day rain (mm), 30-day mean high temperature (°C), indoor plumbing leaks & window material.

Analyses using aggregated variables showed that the presence of multiple mechanical ventilation types (rangehood, bathroom and clothes dryer vented to outdoors) was consistently associated, in a dose-dependent fashion, with less indoor dampness (aORs 0.3 to 0.5, for two or three types of ventilation present; p for trend <0.05 in 2010 and 2015; Table 4.3). Dose-response trends were also demonstrated for BEC defects in all three surveys, with houses with four or five defects being 6.4 to 9.6 times more likely to be characterised as damp (p for trend <0.001). We also found a strong association between overall condition rating (OCR) and indoor dampness with aORs ranging from 20.6 to 47.8 comparing poor versus excellent condition (p for trend <0.001 for all three surveys, Table 3). A consistent dose-response pattern was also found with aggregated subfloor defects, although the trend was statistically significant only in 2010 and 2015 (p for trend <0.01).

Table 4.3. Analysis of aggregated variables of subjective indoor dampness in three house condition surveys.

			2005			2010			2015
			N=565/n=63			N=345/n=91			N=507/n=77
			P=0.0008			P<0.0000			P<0.0000
			R^2=0.11			R^2=0.28			R^2=0.37
	N	*n*	aOR	*N*	*n*	aOR	*N*	*n*	aOR
Ventilation/3 (bath/ cooker/dryer) 0	*239*	*31*	*Ref*	*97*	*40*	*Ref*	*124*	*33*	*Ref*
1	*188*	*24*	1.4 (0.7, 2.6)	*123*	*28*	**0.4 (0.2, 0.8)****	*167*	*31*	0.7 (0.4, 1.5)
2	*113*	*7*	0.7 (0.3, 1.6)	*99*	*19*	**0.4 (0.2, 1.0)***	*183*	*11*	**0.3 (0.1, 0.6)*****
3	*25*	*1*	0.3 (0.4, 2.8)	*26*	*4*	*0.3 (0.1, 1.2)^*	*33*	*2*	0.3 (0.0, 2.0)
Trend			NS			P<0.05			P<0.01
Insulation/3 (roof/ Wall/underfloor or slab) 3	*211*	*12*	*Ref*	*97*	*12*	*Ref*	*115*	*9*	*Ref*
2	*153*	*21*	1.8 (0.8, 4.1)	*135*	*34*	1.6 (0.6, 3.9)	*297*	*41*	1.5 (0.5, 4.3)
1	*173*	*23*	1.6 (0.7, 3.8)	*108*	*44*	*2.3 (0.9, 6.3)^*	*87*	*22*	2.5 (0.7, 8.2)
No insulation	*28*	*7*	*2.9 (0.9, 9.9)^*	*5*	*1*	1.0 (0.1, 12.9)	*8*	*5*	**7.5 (1.1, 49.9)***
Trend			NS			P=0.05			P=0.09
Subfloor/3 (ventilation/ ponding&leaks/groundcover) 0	*188*	*12*	*Ref*	*20*	*3*	*Ref*	*204*	*14*	*Ref*
1	*193*	*25*	1.3 (0.6, 2.9)	*268*	*60*	3.4 (0.8, 14.8)	*136*	*28*	**3.2 (1.3, 7.7)****
2	*162*	*22*	1.4 (0.6, 3.5)	*57*	*28*	**7.3 (1.5, 36.7)***	*144*	*21*	1.8 (0.7, 4.5)
3	*22*	*4*	1.7 (0.4, 7.2)				*23*	*14*	**15.4 (3.8, 62.8)*****
Trend			NS			P<0.01			P<0.01
BEC/5 (Poorer condition of; roof cladding/wall cladding/windows/exterior paint/spouting and guttering)									
0-1	*329*	*19*	*Ref*	*103*	*12*	*Ref*	*229*	*14*	*Ref*
2-3	*175*	*29*	**2.8 (1.5, 5.2)****	*117*	*31*	2.0 (0.8 ,4.6)	*137*	*26*	**3.4 (1.5, 8.0)*****
4-5	*61*	*15*	**3.9 (1.8, 8.8)*****	*64*	*31*	**6.4 (2.4, 16.9)*****	*141*	*37*	**9.6 (3.8, 23.9)*****
Missing				*61*	*17*	*2.4 (0.9, 6.4)^*			
Trend			P<0.001			P<0.001			P<0.001
OCR									
Excellent	*280*	*6*	*Ref*	*117*	*3*	*Ref*	*231*	*5*	*Ref*
Moderate	*195*	*26*	**6.5 (2.6, 16.7)*****	*122*	*29*	**10.5 (2.8, 38.8)*****	*210*	*37*	**8.9 (3.1,26.0)*****
Poor	*90*	*31*	**20.6 (7.7, 55.3)*****	*104*	*59*	**47.8 (12.1, 188.4)*****	*88*	*36*	**37.2 (10.8,127.7)*****
missing									
Trend			P<0.001			P<0.001			P<0.001

N number in subgroup; n number in subgroup with dampness; ^p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001; NS not significant. All models adjusted for surveyor (except 2005 because of collinearity with zone), 30-day rain (mm), 30-day mean high temperature (°C), occupancy & tenure.

4.4.2 Floor and roof joist moisture measurements

Presence of a ground vapour barrier over more than 50% of the ground under the house was associated with a 0.1 to 1.9% reduction in floor joist moisture content, statistically significant in the 2015 survey (p<0.001) and borderline significant in the 2010 survey (p<0.1; Table 4.4). Presence of ponding or leaks was associated with a 0.7 to 2.3% increase in floor joist moisture content, significant (p<0.05) in both the 2005 and 2010 surveys. Poorer condition of the roof cladding was also associated with a small increase (0.4 to 0.6%) in floor joist moisture content, significant ($p<0.05$) only in the 2010 survey (Table 4.4).

Table 4.4. Multiple regression analysis of floor joist moisture measurements in 3 House Condition Surveys.

	2005		**2010**		**2015**	
	N=326		N=285		N=321	
	P<0.0000		P<0.0000		P<0.0000	
	R^2=0.56		R^2=0.60		R^2=0.44	
	n	Coefficient (95% CI)	*n*	Coefficient (95% CI)	*n*	Coefficient (95% CI)
Range hood						
No	*187*	*Ref*	*155*	*Ref*	*166*	*Ref*
Vented to outside	*139*	-0.0 (-0.8, 0.8)	*130*	-0.3 (-0.8, 0.3)	*155*	**0.7 (-0.0, 1.4)***
Vented to roof space						
Bathroom ventilation						
None	*178*	*Ref*	*150*	*Ref*	*134*	*Ref*
Vented to outside	*89*	0.4 (-0.5, 1.3)	*104*	0.1 (-0.4, 0.6)	*142*	0.3 (-0.4, 1.0)
Vented to roof space	*59*	0.3 (-0.7, 1.3)	*31*	0.1 (-0.7, 0.8)	*26*	-0.2 (-1.4, 1.1)
missing					*19*	0.7 (-0.8, 2.3)
Ceiling insulation						
Most	*244*	*Ref*	*154*	*Ref*	*143*	*Ref*
Mid	*52*	-0.3 (-1.3, 0.8)	*78*	0.3 (-0.2, 0.9)	*126*	-0.5 (-1.2, 0.3)
Least	*30*	-0.2 (-1.4, 1.1)	*11*	**1.9 (0.7, 3.2)*****	*16*	-0.2 (-1.8, 1.4)
Missing			*42*	0.2 (-0.5, 0.9)	*36*	-0.9 (-2.0, 0.21)
Subfloor ventilation sufficient						
Yes	*123*	*Ref*	*68*	*Ref*	*89*	*Ref*
No	*203*	**1.1 (0.3, 1.8)****	*192*	**0.6 (0.0, 1.3)***	*195*	0.6 (-0.2, 1.4)
Slab foundation			*25*	-0.5 (-1.5, 0.5)	*37*	0.4 (-0.8, 1.7)
Missing						
Ground cover under house						
Piles & 0-50% ground covered	*237*	*Ref*	*229*	*Ref*	*230*	*Ref*
Piles & >50% ground covered	*6*	-0.1 (-2.6, 2.9)	*31*	*-0.6 (-1.3, 0.1)^*	*60*	**-1.9 (-2.8, -1.0)*****
Slab foundation	*83*	-0.0 (-0.9,0.8)	*25*	*-1.1 (-2.3, 0.0)^*	*5*	**-5.3 (-8.7, -1.9)*****
missing					*26*	-1.2 (-3.2, 0.8)
Ponding /leaks under house						
No	*292*	*Ref*	*222*	*Ref*	*262*	*Ref*
Yes	*34*	**2.3 (0.4, 4.2)***	*63*	**0.8 (0.14, 1.4)***	*59*	0.7 (-0.4, 1.7)
Roof condition rating						
Excellent/Good	*216*	*Ref*		*Ref*	*165*	*Ref*
Moderate/poor/serious	*110*	0.5 (-0.3, 1.2)		**0.6 (0.1, 1.1)***	*150*	0.4 (-0.5, 1.3)
Missing				0.6 (-0.6, 1.7)	*6*	-1.2 (-3.7, 1.3)
Window condition						
Excellent/Good	*206*	*Ref*	*118*	*Ref*	*151*	*Ref*
Moderate/poor/serious	*120*	*0.7 (-0.2, 1.5)^*	*157*	-0.1 (-0.6, 0.4)	*168*	-0.1 (-1.0, 0.8)
Missing			*10*	-0.6 (-1.9, 0.6)	*2*	-2.4 (-6.7, 1.9)
Wall cladding condition						
Excellent/Good	*222*	*Ref*	*55*	*Ref*	*165*	*Ref*
Moderate/poor/serious	*104*	0.1 (-0.8, 1.0)	*218*	0.0 (-0.6, 0.7)	*153*	0.4 (-0.5, 1.3)
Missing						
Cladding type						
Timber weatherboards	*137*	*Ref*	*71*	*Ref*	*102*	*Ref*
Fibre-cement	*34*	0.6 (-0.7, 2.0)	*28*	0.3 (-0.6, 1.1)	*46*	0.5 (-0.6, 1.6)
Brick	*30*	-0.9 (-2. 3, 0.5)	*25*	0.6 (-0.4, 1.5)	*43*	0.0 (-1.2, 1.3)
Mixed/other	*125*	-0.1 (-1.0, 0.8)	*161*	0.2 (-0.4, 0.8)	*130*	0.5 (-0.4, 1.3)
Spouting condition						
Excellent/good	*253*	*Ref*	*176*	*Ref*	*185*	*Ref*
Moderate/poor/serious	*73*	0.5 (-0.4, 1.5)	*94*	-0.1 (-0.6, 0.5)	*134*	**0.9 (0.0, 1.8)***
Missing			*15*	**1.2 (0.1, 2.3)***	*2*	*-4.0 (-8.2, 0.4)^*

p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001; All models adjusted for surveyor (except 2005 because of collinearity with zone), 30-day rain (mm), 30 day mean high temperature (°C), climate zone, number of occupants, heating (gas/electric/enclosed fire), dryer ventilation, plumbing leaks indoors, double glazing & missing flashings.

Table 4.5. Multiple regression analysis of ceiling joist moisture measurements in 3 House Condition Surveys.

		2004		**2010**		**2015**
		N=482		N=373		N=416
		P<0.0000		P<0.0000		P<0.0000
		R^2=0.24		R^2=0.28		R^2=0.21
	n	Coefficient (95% CI)	*n*	Coefficient (95% CI)	*n*	Coefficient (95% CI)
Age of house						
Pre 1930	*81*	*Ref*	*47*	*Ref*	*52*	*Ref*
1930-1979	*267*	**-0.6 (-1.1, - 0.1)****	*183*	-0.7 (-1.7, 0.4)	*233*	-0.1 (-1.8, 1.6)
Post 1980	*132*	**-0.9 (-1.6, -0.2)***	*123*	-0.9 (-2.2, 0.4)	*131*	0.5 (-1.8, 2.7)
Open fireplace						
No	*390*	*Ref*	*339*	*Ref*	*393*	*Ref*
Yes	*92*	0.1 (-0.3, 0.5)	*34*	0.1 (-1.0, 1.3)	*23*	**2.5 (0.3, 4.7)***
Subfloor ventilation sufficient						
Yes	*125*	*Ref*	*58*	*Ref*	*71*	*Ref*
No	*241*	0.2 (-0.1, 0.6)	*193*	0.7 (-0.3, 1.7)	*192*	-0.1 (-1.5, 1.4)
Slab foundation	*116*	0.2 (-0.3,0.6)	*122*	0.4 (-0.7, 1.6)	*153*	-0.4 (-2.0, 1.2)
Missing						
Roof material						
Metal	*317*	*Ref*	*274*	*Ref*	*298*	*Ref*
Concrete/clay tile	*160*	**0.9 (0.5,1.2)*****	*91*	**1.2 (0.4, 2.0)*****	*96*	0.3 (-1.0, 1.6)
Missing/mixed/other	*5*	-0.1 (-1.4,1.3)	*8*	0.9 (-1.3, 3.1)	*22*	-0.1 (-2.5, 2.4)
Roof condition rating						
Excellent/Good	*353*	*Ref*	*216*	*Ref*	*246*	*Ref*
Moderate/poor/serious	*129*	-0.1 (-0.4, 0.2)	*138*	0.3 (-0.4, 1.1)	*160*	1.0 (-0.2, 2.2)
Missing			*19*	1.1 (-0.4, 2.5)	*10*	-0.4 (-3.7, 2.9)
Window condition						
Excellent/Good	*326*	*Ref*	*189*	*Ref*	*151*	*Ref*
Moderate/poor/serious	*156*	-0.2 (-0.5, 0.1)	*173*	0.6 (-0.2,1.4)	*168*	-0.6 (-1.9, 0.7)
Missing			*11*	0.4 (-1.5, 2.2)	*2*	-1.3 (-6.5, 4.0)
Cladding type						
Timber weatherboards	*166*	*Ref*	*77*	*Ref*	*101*	*Ref*
Fibre-cement	*45*	-0.4 (-1.0, 0.2)	*29*	-0.5 (-1.9, 0.9)	*51*	0.6 (-1.3, 2.6)
Brick	*80*	**-0.6 (-1.1, -0.1)***	*46*	0.4 (-0.8, 1.6)	*87*	*-1.5 (-3.2, 0.3)^*
Mixed/other	*191*	**-0.4 (-0.8, -0.0)***	*221*	-0.7 (-1.6, 0.2)	*177*	-0.0 (-1.4, 1.4)

^p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001. Models adjusted for surveyor (except 2005 because of collinearity with zone), 30-day rain (mm), 30-day mean high temperature (°C), house age category, number of occupants, heating (gas/electric/open fire) & wall insulation.

There were few consistent associations between moisture content of the roof framing and other variables, although roofs that were clad with concrete or brick tiles were associated with an increase in moisture levels (0.9% to 1.2%) compared to roofs clad with a metal cladding material; this association was statistically significant ($p<0.001$) in both the 2005 and 2010 surveys (Table 4.5). Also, compared to the oldest houses (built before 1930), moisture content of roof framing in newer houses was progressively lower (1930s to 1970s, -0.6% to -0.7%; and 1980 and newer -0.9%) in the 2005 and 2010 surveys, although this relationship was significant ($p<0.05$) only in the 2005 survey.

Combined subfloor defects were consistently associated with increased floor joist moisture (1.2% to 3.7%, $p<0.01$ for houses with two or three (of three) defects; Table 6). BEC defects were also associated with increased moisture content in the floor joists (1.8% and 1.5%) for houses with two or three (of five) building envelope defects present, in 2005 and 2015 respectively, with a significant trend shown in 2015 ($p<0.01$; Table 4.6). Using the assessors' overall condition rating (OCR), a significant trend with moisture content in the floor joist was shown in the 2015 survey ($p<0.05$), but the relationship was weaker than for BEC variables. We also found that the presence of less insulation types was associated, in a dose-dependent fashion, with increased moisture content in roof joists in the 2005 survey (Table 4.6); this trend was significant also in 2010, but no association was observed in the 2015 survey.

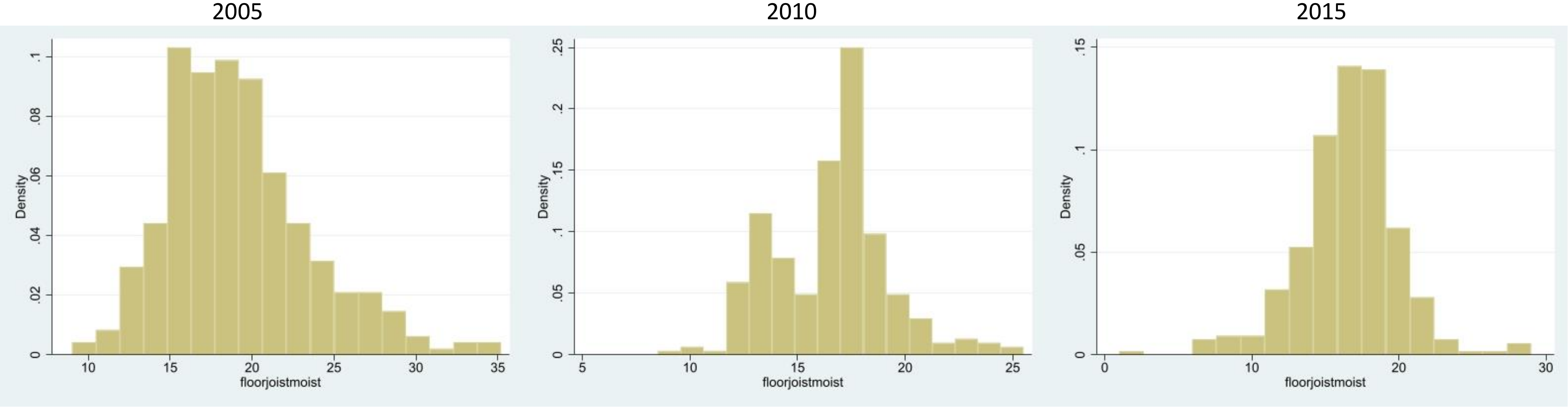
Table 4.6. Analysis of aggregated variables of ceiling and floor joist moisture in three house condition surveys.

	Ceiling Joist Moisture						Floor Joist Moisture					
	2004		2010		2015		2005		2010		2015	
	N=482		N=373		N=400		N=326		N=285		N=310	
	P<0.0000		P<0.0000		P<0.0000		P<0.0000		P<0.0000		P<0.0000	
	R^2=0.21		R^2=0.21		R^2=0.21		R^2=0.52		R^2=0.59		R^2=0.38	
	n	Coefficient (95% CI)	*n*	Coefficient (95% CI)	*n*	Coefficient (95% CI)	*n*	Coefficient (95% CI)	*n*	Coefficient (95% CI)	*n*	Coefficient (95% CI)
Ventilation/3 (bath/ cooker/dryer)												
No mechanical ventilation	*202*	*Ref*	*104*	*Ref*	*10*	*Ref*	*149*	*Ref*	*91*	*Ref*	*90*	*Ref*
1/3 ventilation	*161*	-0.1 (-0.4, 0.2)	*125*	-0.5 (-1.4, 0.3)	*126*	-0.2 (-1.4, 1.0)	*105*	0.4 (-0.4, 1.3)	*107*	-0.3 (-0.8, 0.3)	*106*	0.0 (-0.8, 0.9)
2/3 ventilation	*96*	0.0 (-0.4, 0.4)	*115*	0.1 (-0.8, 1.0)	*150*	0.3 (-0.9, 1.4)	*53*	0.3 (-0.7, 1.4)	*73*	0.1 (-0.5, 0.7)	*95*	0.2 (-0.7, 1.1)
3/3 ventilation	*23*	0.4 (-0.2, 1.1)	*29*	-0.4 (-1.8, 1.0)	*23*	0.5 (-1.7, 2.6)	*19*	1.2 (-0.4, 2.8)	*14*	0.1 (-1.1, 1.2)	*19*	0.4 (-1.1, 2.0)
Trend		NS		NS		NS		NS		NS		NS
Insulation/3 (roof/ wall/underfloor or slab)												
3/3 insulation	*174*	*Ref*	*21*	*Ref*	*94*	*Ref*	*74*	*Ref*	*48*	*Ref*	*38*	*Ref*
2/3 insulation	*133*	**0.8 (0.5, 1.2)*****	*293*	0.0 (-1.4,1.4)	*221*	*-1.1 (-2.4, 0.2)^*	*91*	-0.6 (-1.6, 0.4)	*123*	**-0.7 (-1.3, -0.0)***	*202*	**-1.2 (-2.4, -0.1)***
1/3 insulation	*150*	**0.9 (0.5, 1.3)*****	*59*	0.3 (-1.3,1.9)	*77*	-0.8 (-2.4, 0.8)	*137*	-0.6 (-1.5, 0.4)	*109*	-0.5 (-1.2, 0.2)	*65*	-0.8 (-2.2, 0.5)
No insulation	*25*	0.6 (-0.2, 1.3)			*8*	-1.4 (-4.8, 2.0)	*24*	-0.5 (-2.0, 1.1)	*5*	1.0 (-0.8, 2.8)	*5*	0.8 (-2.1, 3.6)
Trend		P<0.01		P<0.05		NS		NS		NS		NS
Subfloor/3 (ventilation/ ponding&leaks/groundcover)												
No subfloor defects	*155*	*Ref*	*128*	*Ref*	*145*	*Ref*	*21*	*Ref*	*25*	*Ref*	*32*	*Ref*
1/3 subfloor defects	*159*	0.0 (-0.3, 0.3)	*120*	0.0 (-0.9, 0.9)	*109*	*-1.2 (-0.0, 2.4)^*	*164*	0.4 (-0.9,1.7)	*203*	*0.7 (-0.1,1.5)^*	*107*	0.9 (-0.3,2.1)
2/3 subfloor defects	*146*	0.3 (-0.2, 0.7)	*103*	0.2 (-0.8, 1.1)	*127*	-0.3 (-1.5, 0.9)	*125*	**1.9 (0.5,3.2)****	*57*	**1.2 (0.3,2.2)****	*148*	**1.6 (0.5, 2.8)****
3/3 subfloor defects	*22*	-0.0 (-0.8, 0.7)	*22*	0.1 (-1.5, 1.7)	*19*	1.1 (-1.2, 3.3)	*16*	1.1 (-0.9,3.0)			*23*	**3.7 (2.0, 5.4)*****
Trend		NS		NS		NS		P<0.01		P=0.01		P<0.001
BEC/5 (Poorer condition of; roof cladding/wall cladding/windows/exterior paint/spouting and guttering)												
0-1 condition deficit	*284*	*Ref*	*118*	*Ref*	*192*	*Ref*	*169*	*Ref*	*72*	*Ref*	*169*	*Ref*
2-3 factor deficit	*147*	-0.0 (-0.4, 0.3)	*123*	0.1 (-0.8, 0.9)	*109*	**1.6 (0.4, 2.8)****	*115*	-0.0 (-0.8, 0.8)	*110*	*0.5 (-0.1, 1.1)^*	*115*	**0.9 (-0.0, 1.8)***
4-5 factor deficit	*51*	*-0.5 (-1.0, 0.02)^*	*70*	0.6 (-0.4, 1.7)	*99*	0.5 (-0.9, 2.0)	*42*	**1.8 (0.7, 2.9)*****	*58*	0.3 (-0.4, 1.0)	*42*	**1.5 (0.5, 2.5)*****
missing			*62*	0.1 (-0.9, 1.1)					*45*	0.5 (-0.2, 1.2)		
Trend		NS		NS		NS		P=0.1		NS		P<0.01
OCR												
Excellent	*240*	*Ref*	*98*	*Ref*	*188*	*Ref*	*134*	*Ref*	*69*	*Ref*	*114*	*Ref*
Moderate	*165*	-0.2 (-0.5, 0.2)	*94*	0.6 (-0.3,1.5)	*160*	0.5 (-0.7, 1.7)	*128*	0.1 (-0.8,0.9)	*71*	0.1 (-0.6,0.8)	*139*	*0.8 (-0.1,1.6)^*
Poor	*77*	0.2 (-0.2, 0.7)	*87*	**1.3 (0.2, 2.3)***	*68*	1.0 (-1.6, 1.8)	*64*	-0.2 (-1.30.8)	*76*	0.5 (-0.3,1.2)	*67*	**1.3 (0.3,2.4)***
missing			*94*	0.1 (-0.9,1.1)					*69*	**-0.8 (-1.6,-0.1)***		
trend		NS		NS		NS		NS		NS		P<0.05

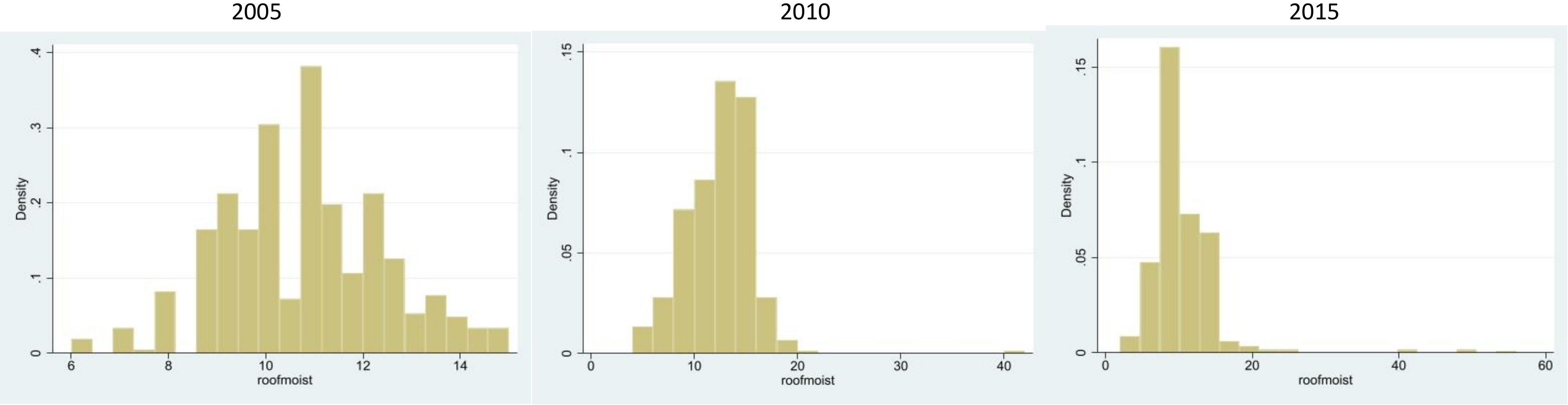
^p≤0.10; *P≤0.05; **p≤0.01; ***p≤0.001; NS not significant. All models adjusted for surveyor (except 2005 because of collinearity with zone), 30-day rain (mm), 30-day mean high temperature (^{o}C), occupancy & tenure.

Figure 4.1. Histograms showing moisture content in floor and ceiling joists

Floor joist


2005 2010 2015

Ceiling joist


2005 2010 2015

4.5 Discussion

This study showed that specific subfloor and BEC defects were associated with increases in both subjectively assessed indoor dampness and objectively measured moisture in floor joists, whereas other house characteristics, such as fewer ventilation and insulation factors, more occupants, tenure type (rented), and poorer inspector-assessed overall condition rating (OCR), were associated only with increased indoor subjective dampness but not with either floor joist or ceiling joist moisture content. Older houses, and houses with concrete or brick tile roofs (compared to metal cladding materials) were associated with higher moisture content readings in the ceiling joist, but not with either subjective indoor damp or floor joist moisture.

4.5.1 Subjective indoor dampness

Building envelope condition defects were generally associated with increased indoor dampness, with a significant dose-response pattern observed for the aggregated variable in all three surveys. Consistent with this, and using data from the same three surveys, we have previously shown a similar association between BEC and both indoor visible mould and musty odour (both inspector-assessed) [24]. A study from Quebec that assessed self-reported dampness in 2097 student dormitory rooms also found a dose-response association between poor repairs and increased dampness [16], whilst two other studies found increased mould in houses with poor repairs [23, 41]. Unlike our study that assessed associations with individual aspects of poor repairs/building defects (see Appendix 2), these studies did not further characterise “poor repair”, thus hampering the development of specific interventions beyond “more regular maintenance”.

In our study, the presence of insulation in fewer parts of the building envelope (ceiling, underfloor and wall cavity) was associated with increased indoor dampness. This is consistent with a large survey from Canada, which found that “improved insulation” was associated with reduced self-reported indoor dampness [18]. This is likely due to higher indoor temperatures, with warm air requiring fewer air changes to reduce indoor moisture [43]. Similar to our findings, two intervention studies reported reduced dampness following installation of insulation in ceiling cavities [19, 44]. On the other hand, another study, involving a sample of homes with no wall or ceiling insulation and using a three-point scale for inspector reported dampness (dry/a little damp/very damp), showed that although underfloor insulation was inversely associated with the exposure category “a little damp”, it did not reduce the odds of houses being categorised as “very damp” [43]. In addition to considering associations with indoor dampness indicators/measurements and ventilation and insulation separately, we also assessed the same associations using a combined insulation/ventilation variable (High/high, high/low, low/high, low/low insulation/ventilation). This showed that none of these pairings were consistently or significantly associated across surveys to subjective dampness or measured moisture (data not shown), suggesting that there was no clear interaction between insulation and ventilation.

A dose-response pattern of increased dampness with more (aggregated) subfloor defects in all three surveys was observed, with the presence of ponding and leaks under the house being significantly and independently associated also in the initial multivariate analysis (2010) using individual (non-aggregated) variables. This may be the due to warm indoor air creating a “stack effect”, resulting in damp air from the subfloor space to be drawn upwards, thus infiltrating into the interior [42]. In contrast to our current findings, a previous study conducted by this research team, using data from the same three surveys, showed no association between subfloor defects and visible mould [24]. The reason for this difference may be that subjective dampness and damp subfloor conditions are more closely associated with climatic conditions at the time of the survey than the presence of visible mould, which is more likely to be related to conditions over a longer time period.

To our knowledge, no other studies reported on the relationship between specific subfloor defects and indoor dampness. However, several studies have assessed associations with the presence of a subfloor (pile foundations), the results of which have been inconsistent. In particular, two studies, one from the USA and one from Finland, reported more indoor dampness for houses with a subfloor [44, 20] while a study from Sweden found the opposite [15]. A large study assessing associations with wet/dry basements reported that wet basements increased the risk of self-reported visible mould [45], however, this finding is not directly comparable to our study as basements with internal access and subterranean walls, are very different from houses constructed with pile foundations and subfloor spaces that do not have direct access to the house, as was the case for most of the houses in our sample.

Mechanical ventilation (extractor fans) was associated, in a dose-dependent fashion, with less dampness. The presence of a rangehood over the cooker was particularly effective, reducing the odds of dampness to <50%, as observed in two of the three surveys. Our earlier study showed a similar dose-response for aggregated ventilation and reduced indoor mould, although no significant association was found when considering the presence of a rangehood by itself [24]. Other large surveys also found that the presence of a rangehood or kitchen fan was associated with a reduction in visible mould [45] or self-reported indoor dampness [22]. Similarly, a survey found that the presence of whole-house mechanical exhaust ventilation was associated with an approximately 50% reduced risk of floor moisture (visible damp patches) and condensation [15]. Similar effects of rangehoods and/or bathroom extractor fans on indoor damp and mould have also been reported in studies from Canada and China [16, 46]. Mechanical ventilation reduces moisture by increasing the number of air changes per hour, thus replacing moist indoor air with air from outside that is generally drier [42]. Due to only a small number of houses in our sample having whole house ventilation systems, we were unable to assess the effectiveness of this compared to having extractor fans only in those rooms where most moisture is generated (kitchen and bathroom).

In the current study we found a strong dose-response association between the overall condition rating (OCR) of the house and indoor dampness, with more indoor dampness in poorly- compared to well-maintained houses. This is similar to what we found previously for indoor mould and musty odour [24] and is consistent with other studies showing that an overall need of construction repairs or maintenance is associated with increased dampness or mould [16, 41, 47]. Since dampness and mould were considered by assessors as one of the indicators of a poor overall housing condition, this is perhaps not surprising. However, we also found strong associations with BEC, which was based on specific envelope components and did not include indoor dampness and mould.

The positive association between increased indoor dampness and fibre-cement cladding is of interest, particularly since questions surrounding weathertightness have been raised, and are currently being considered in the courts, in New Zealand. However, weathertightness was not assessed in this study, so we cannot ascertain with certainty whether the observed associations are related to this.

4.5.2 Moisture measurements

Ceiling joists of older houses and those with roofs clad with concrete or clay tiles were shown to have greater moisture content. The association with older houses may be due to the construction methods used to connect walls and ceilings in older New Zealand homes being less airtight compared to current methods [48], potentially resulting in indoor moisture infiltrating into the roof from activities inside [49]. Alternatively, or in addition, it may be due to residual confounding. In particular, although analyses were controlled for roof cladding condition, correctly identifying the condition of the roofs is difficult from a simple visual inspection, and hidden defects, such as cracked grouting and tiles, or loosening around nails and rust underneath joins, which are more likely in older houses, may contribute to this increased moisture in the roof space. We speculate that the association with different roofing materials may be related to differential solar heat adsorption and airtightness properties of tiled/concrete and sheet metal roofs. However, we were not able to assess this in the current study.

The strong association between subfloor defects (insufficient ventilation, ponding or leaks and lack of ground moisture barrier) and increased floor joist moisture content was expected, due to the proximity of the moisture sources (and modulating parameters) to where the measurements were taken. These three subfloor factors have previously been identified as related to high indoor dampness [50, 51]; however, to our knowledge, no other studies have assessed associations between house characteristics and objectively measured moisture in the subfloor framing, while also adjusting for other known contributors to indoor dampness. Our results show the apparent additive nature of these three factors, as reflected in the significant trend of increasing frequency of subfloor defects with increasing floor joist moisture. This is particularly apparent in the 2015 survey, the first of our three surveys to include more than a handful of houses with a ground moisture barrier present.

An increase in the number of building envelope defects in the aggregated BEC was associated with increasing moisture content in the floor joist. Two mechanisms may explain this. Firstly, water infiltrating the envelope via defects in the cladding may collect at the base of the wall framing and sub floor framing due to gravity, where it can be transported through flooring materials to floor joists via capillary action. Secondly, water accumulating around the base of the house due to defects in the storm water system may create a damp microclimate around the subfloor space and structure. Unlike the BEC, the inspectors' OCR did not show consistent associations with floor or roof joist moisture content, which suggests that a general indicator such as OCR may not be sufficiently specific as a proxy of moisture. To our knowledge, no other studies have assessed associations between house condition or repair and measured moisture, either in framing or indoors, although one study demonstrated a link between older houses (a proxy for poor repair) and increased relative humidity indoors [27].

Increased mechanical ventilation, which was strongly associated with reduced indoor dampness here, as well as with both mould and musty odour in our earlier study [24], was not clearly associated with measured moisture content in the floor or roof joists. As wall cavity and framing moisture is generally considered to be strongly affected by the infiltration of moisture produced indoors by occupants [42, 52], we had expected an inverse association between insulation and ventilation and floor and ceiling joist moisture content. However, this was not the case. This suggests that floor and ceiling joist moisture content may be less affected by moisture from the indoor environment; instead it may be more affected by the impact of moisture originating from outdoors (see section 4.1), although this could not be confirmed in this study.

The significant trend with fewer aggregated insulation factors and higher ceiling joist moisture content in 2005 and 2010 (Table 7) is similar to what we found for subjectively measured indoor dampness (Table 4), and visible mould and mouldy odour, as reported earlier [24]. The reasons for this may be the same as described for subjectively measured moisture (see above); however, the fact that ceiling insulation was not independently associated with ceiling joist moisture in the non-aggregated analysis, suggests that this result may reflect confounding with some other related construction factor. No clear association between insulation and floor joist moisture was found.

This study also found that that poorer roof condition was associated with increased floor joist moisture. The reasons for this are unclear.

A further analysis was conducted looking specifically at recorded insulation defects, including gaps, settling, poor fit and other unspecified damage. Presence of these defects was summed (with no insulation present coded as the highest category) and the index tested against dampness and moisture measurements. The relationship of this index with dampness and moisture measurements was inconsistent across surveys (data not shown).

4.5.3 Limitations.

An important weakness of the study was the lack of data on behaviour of the occupants, which may confound associations between house characteristics and indoor dampness. However, occupant behaviour may not have been a strong confounder as results were reasonably consistent between surveys despite taking place in different seasons (the 2005 survey was conducted almost entirely in summer and the 2010 almost entirely in winter and spring) when occupant behaviours were likely very different. Furthermore, as associations were relatively strong and showed dose-response patterns, it is unlikely to be explained entirely by confounding. Nonetheless, confounding by occupant behaviour cannot be excluded.

Inspector-rated indoor dampness (based on the subjective feeling or sensation of indoor humidity or dampness) in our study was not entirely comparable to similar reported outcomes in the international literature, where it is often based on a visual inspection, including damp stains, patches and sometimes condensation [16, 21, 22, 44, 53]. Similarly, our study focussed on a specific style of housing, namely timber-framed houses, and was conducted in a temperate maritime climate, characterised by a narrow range of temperatures and high humidity year-round. This is different from many other studies, somewhat limiting the comparability of our results. Nonetheless, despite these differences, many of the associations between household characteristics and dampness observed in our study were similar to those reported in the literature. Additionally, although moisture measurement instruments were calibrated at the start of the study, they were not recalibrated, so we cannot ascertain that instrument drift did not occur, nor to what extent such drift may have affected our results.

Our results, particularly in unaggregated analyses, were sometimes inconsistent across the three samples. This may be due to the relatively small number of houses with particular characteristics in some surveys (e.g. presence of a ground cover vapour barrier in the first two surveys) resulting in reduced study power for some analyses. Also, a lack of rental and poorly maintained houses in the first (2005) survey may have resulted in some associations not being observed in this survey – particularly those related to the condition of the house. Furthermore, climate differences due to sampling at different times of the year has likely impacted on the proportion of homes with dampness, again limiting the statistical power for some surveys. Finally, not being able to control the analyses for human behaviour (as discussed above), may have differentially affected the results for each of the surveys.

4.5.4 Conclusions

Our study showed that subfloor and building envelope defects were associated with both subjectively assessed indoor dampness and objectively measured floor joist moisture content, whilst insulation, ventilation, occupancy and tenure were associated only with subjectively assessed indoor dampness. These results provide important new insights that may facilitate the development of more effective interventions to reduce indoor dampness. However, significant knowledge gaps remain in understanding of how human behaviour mediates the relationship between house characteristics and indoor dampness and building moisture. Future work taking into account human behaviour (e.g. use of heaters and ventilation practices) and across a wide range of climatic zones is needed to ensure that interventions are optimally effective for all homes and living conditions.

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5 Interrelationships among five indoor dampness measures across three New Zealand house condition surveys.

Phoebe Taptiklis, Robyn Phipps, Mark Jones, Jeroen Douwes

To be submitted for publication

5.1 Abstract

Three iterations (2005, 2010 and 2015) of the New Zealand House Condition Survey were used to assess the interrelationships among five different indoor dampness measurements (objectively measured moisture content in floor and ceiling joists, and inspector-assessed indoor visible mould, subjective dampness and musty odour) using linear and logistic regression. The exent of visible mould (None, specks, patches, large patches) was not associated with either floor or ceiling joist moisture in univariate analysis. It was, however, associated, in a dose-dependent manner, with both subjective dampness and mouldy odour, and this association was independent of associations of measured moisture in multivariate analysis. The highest category of mould was associated with 3-40 times the odds of subjective dampness ($p<0.01$), and 1.8 and 8.5 times the odds of musty odour. Ceiling and floor joist moisture measurements were significantly correlated (r 0.64 to 0.85 ($p<0.05$)). In conclusion, while extent of visible mould was strongly associated with subjective dampness and musty odour, and these were both associated with framing moisture, extent of visible mould was unassociated with framing moisture. These results suggest that until the

causes of dampness are more fully understood multiple dampness assessments give a clearer picture than any single measurement alone.

5.2 Introduction

Indoor dampness is a risk factor for asthma, rhinitis and acute respiratory illnesses, including conditions such as respiratory syncytial virus (RSV), bronchiolitis and bronchopneumonia [1-3]. In fact, a large meta-analysis suggests that indoor dampness may increase the risk of respiratory illness by 30 to 50% [4]. Similarly, a case-control study among New Zealand infants attributed almost one in five cases of respiratory infections to damp housing [5]. However, associations have not always been consistent, particularly for studies involving objective measurements of moulds [6] and/or quantitative moisture/humidity assessments [7, 8]. In contrast, subjectively reported dampness is generally more consistently associated with respiratory symptoms [2, 9, 10], but these measures cannot easily be standardised, thus impeding the development of robust indoor dampness thresholds to identify risk.

The reasons why objective measures (e.g. viable mould spore counts and relative humidity) are often inconsistently associated with health outcomes are not clear but may be due to often small numbers of samples collected combined with potentially large measurement error due to considerable temporal and spatial variance [10, 11]. Alternatively, these measures may only represent one specific, and possibly not the most relevant, aspect of indoor dampness, with symptoms potentially resulting from a combination of dampness-associated exposures.

Although subjective measures of indoor dampness appear more consistently associated with respiratory symptoms, it is not clear which specific measures (e.g. signs of dampness, visible mould and mould odour) most accurately reflect causal exposures, and whether these different measures represent distinct exposure situations. There is some evidence that summing several measures of dampness may result in stronger associations with health outcomes, providing support for each measure representing, at least in part, distinct aspects of the causal exposures(s), although it cannot be excluded that it simply represents a greater dose of the same exposure. For example, a large multi-centre study, involving 40,000 children from China, showed that cumulative dampness indicators were positively associated with asthma symptoms [12] in a dose-dependent fashion. Similarly, a study in Japan showed a significant trend of increasing symptoms of “sick house syndrome” (SHS) with increasing cumulative dampness measures [13] and a study from Sweden reported more respiratory symptoms with an increase in cumulative signs of dampness [14].

The current study used data from three consecutive New Zealand House Condition surveys (2005, 2010, 2015) to assess the interrelationships among visible mould, subjective dampness, musty odour, and objective measurements of moisture content in floor and ceiling joists.

5.2.1 Methods

5.2.1.1 House Condition Surveys

The New Zealand House Condition Survey is conducted by the Building Research Association of New Zealand (BRANZ) and has been undertaken approximately every five years since 1994 [28]. The current study used data collected from the three most recent surveys i.e. 2005, 2010 and 2015. The sampling methodology is described in detail elsewhere [15-17]. Briefly, the three surveys were predominantly restricted to single family, timber-framed dwellings, with no apartments included, which were uncommon in New Zealand during this period.

While using almost identical assessment protocols, there were some differences between the three surveys: in 2005, the sample was limited to only owner-occupied houses in the three largest New Zealand cities and outlying regions (Auckland and Wellington in the North Island, and Christchurch in the South Island); for the 2010 and 2015 surveys, rental houses and houses located in other cities and rural towns were included, and a sampling structure was developed to capture a more representative sample of dwellings. The sampling structure for the 2010 and 2015 surveys involved dividing the country into 13 strata, 11 of which corresponded to urban areas, with the remaining two strata involving the rest of the North Island, and the rest of the South Island. Cluster-sampling was used within strata based on census mesh-blocks (smallest statistical area unit). Also, from 2010, additional training for home inspectors was provided to increase the consistency of dampness, mould and condition assessments; this involved a day of theoretical training, including how to conduct moisture assessments, followed by supervised inspections. From 2010, the subjective assessment of musty odour was also added.

5.2.1.2 Moisture measurements

Percentage moisture content (%MC) was measured using a two-pronged electrical resistance meter (Protimeter CEM DT-125) in the timber structural framing of houses where access to the roof space or subfloor was available. In the ceiling joists, a single measurement was taken. In floor joists, two measurements were taken from different joists at least 5m apart. This was in recognition that unseen leaks may have led to small areas with high moisture that are not reflective of overall moisture level of floor joists. The same method was not used in the ceiling due to inaccessibility. For the purpose of this study the two floor joist measurements were averaged. To assess reproducibility, we measured the (Pearson) correlation between both floor joist measurements.

5.2.1.3 Subjective indoor dampness

Dampness was assessed (subjectively) by inspectors after completing the indoor inspection using the following categories: dry, some damp, and damp throughout [28]. The 2010 survey included a high number of missing values for the dampness variable (29%), particularly for the earliest period of data collection. Comparing houses with and without missing data for dampness showed that key home characteristics (i.e. house age, presence of insulation, presence of mechanical ventilation, number or type of heaters and visible mould) did not appreciably differ between both groups (data not shown), suggesting that missing data is unlikely to have resulted in a systematic bias of our sample. Results reported in the tables are based on houses with no missing data for the main outcome variables (i.e. subjective dampness and measured moisture in ceiling and floor joists).

5.2.1.4 Visible mould

Visible mould was reported for each room in the house separately using a 5-point scale of mould severity (none, specks, patches, large patches, extensive). Inspectors' training (2010 and 2015 only) to assess indoor mould involved using photographs of homes with different levels of indoor mould to calibrate the level of severity. Data on mould severity by room was aggregated to a single outcome for the whole house ("mould in the whole house") based on the highest reported level for any room in that house. Another mould severity variable was defined using the same approach for living and bedrooms only ("mould in living and bedrooms").

5.2.1.5 Musty odour

Musty odour was recorded for the whole house (and not for individual rooms) as a dichotomous variable (yes/no). Training on this aspect was conducted during supervised visits.

5.2.1.6 Climate data

Rainfall and temperature. For each house, we obtained twenty-four-hour rainfall and daily maximum temperatures for a 30-day period prior to the date of the survey. Data was sourced from the National Climate database [40] from the weather station closest to the house (generally within <10 km). Data were expressed as 30-day total rainfall (mm) and mean 30 daily maximum temperature (°C).

5.2.1.7 Data analyses

Analyses were conducted using STATA 15 (StataCorp LP, TX, USA) for each survey separately. Linear regression was used to assess associations between mould severity and floor and ceiling joist moisture measurements. We also conducted logistic regression to assess associations between mould severity and subjective indoor dampness (in the whole house). For this purpose, subjective dampness was dichotomised into any dampness versus no dampness. We also conducted the same analyses using musty odour (yes/no) as the dependent or outcome variable. We subsequently conducted multivariate analysis, mutually adjusting for other co-variables (floor and ceiling joist moisture, and in the analysis of musty odour, for extent of subjective dampness in the whole house), to test whether associations were independent of one another Visible mould was chosen as the explanatory variable for all of the regression analyses, since it is one of the most commonly reported outcomes and because it had a scale of severity to test dose-response associations with. Moisture measurements were also included in multivariate regression analysis with subjective dampness and musty odour in order to test for independence of the associations with visible mould.

Due to the very small number of observations in the two highest categories of mould in the whole house (“large patches” and “extensive”), these were combined, and mould was assessed as a four-point ordinal variable, except for the 2004 survey, where categories were combined to create a three-point variable (none/specks/patches and greater), again due to low numbers in the highest categories. Using trend-analyses we measured whether there were dose-response associations between indoor mould and the two outcome variables i.e. subjective dampness and musty odour. This was done by repeating the same analysis with the mould variable included as a continuous variable instead of a categorical variable.

Many houses did not have moisture measurement data for both floor and ceiling joists (this was due to accessibility for assessors undertaking these measurements as well as many houses having concrete slab foundations, instead of floor joists), resulting in 42% of the observations being dropped from the full multivariate analysis due to missing data. Therefore, multivariate analyses were repeated without the floor joist measurement (for which we had the largest number of missing data), to test the robustness of the associations found in the full multivariate model that included floor joist measurements, but was done on a smaller number of houses (due to missing data in floor joist measurements). Collinearity between independent variables was assessed by calculating variance of inflation factors, and none were >1.5.

Finally, the two floor joist measurements from each house were plotted on scatter plot graphs with a linear regression line fitted to visualise the association between both measurements for each survey separately. Floor and ceiling joist measurements were also plotted (with an overlaid linear regression line) against each other and stratified for survey iteration and climate zone. Pearson's correlations were also calculated for these measurements.

5.3 Results

Houses in the sample were similar across the three surveys in most physical aspects including age categories, cladding and roof type (Table 5.1). There were differences due to the first survey not including rental houses and including more well-maintained houses as well as somewhat more houses with timber weatherboard cladding and fewer with concrete slab foundations (Table 5.1). There were also important differences in the surveys in terms of season when the data were collected, with the first survey conducted almost entirely in summer, the second (2010) almost entirely in winter and spring, and the third (2015) more evenly spread, although lacking winter observations (Table 5.1).

Table 5.1. Sample characteristics

	2005 (565 houses)	***2010 (491 houses)***	***2015 (560 houses)***
Age category			
Pre 1930	*87* (15)	*58* (13)	*62* (11)
1930-1979	*307* (55)	*242* (52)	*294* (53)
1980 and older	*167* (30)	*163* (35)	*204* (36)
Maintenance Category			
Well maintained	*280* (50)	*125* (25)	*243* (44)
Reasonably maintained	*195* (35)	*127* (26)	*220* (39)
Poorly maintained	*85* (15)	*112* (23)	*96* (17)
Missing	*5* (1)	*127* (26)	
Tenure			
Rented	-	*108* (22)	*149* (27)
Owner occupied	*565* (100)	*383* (78)	*411* (73)
Occupants			
1 to 2	*273* (48)	*277* (56)	*336* (60)
3 to 4	*213* (38)	*167* (34)	*175* (31)
5 or more	*63* (11)	*47* (10)	*49* (9)
Missing	*16* (3)		
Bedrooms			
1 to 2	*35* (6)	*74* (15)	*104* (19)
3 to 4	*489* (87)	*392* (80)	*422* (75)
5 or more	*41* (7)	*23* (5)	*32* (5.5)
Missing			*2* (0.5)
Foundation Type			
Piles	*285* (50)	*314* (64)	*339* (61)
Concrete slab	*280* (50)	*177* (36)	*221* (39)
Cladding Type			
Timber weatherboard	*186* (33)	*97* (20)	*128* (23)
Fibre cement	*55* (10)	*43* (9)	*66* (12)
Brick	*86* (15)	*61* (12)	*110* (20)
Mixed/other	*238* (42)	*290* (59)	*256* (46)
Roof Type			
Metal roof	*372* (66)	*287* (58)	*409* (73)
Concrete/clay tiles	*183* (32)	*201* (41)	*121* (22)
Other	*10* (2)	*3* (1)	*30* (5)
Survey season			
Summer (December-February)	*540* (96)	*50* (10)	*172* (31)
Autumn (March-May)	*10* (2)	-	*149* (27)
Winter (June-August)	-	*56* (12)	*1* (0)
Spring (September-November)	*15* (3)	*383* (78)	*238* (43)
Climate zone			
North	*304* (54)	*161* (33)	*183* (33)
Mid	*111* (20)	*227* (46)	*159* (28)
South	*150* (26)	*101* (21)	*218* (39)
30-day rain			
0-50mm	*302* (53)	*206* (42)	*308* (56)
51-100mm	*212* (38)	*104* (21)	*199* (36)
101-150mm	*44* (8)	*70* (14)	*41* (7)
151mm or more	*7* (1)	*107* (22)	*6* (1)
30-day temp (average)			
<15^{o}C	*0*	*177* (36)	*48* (9)
15.1-20^{o}C	*183* (32)	*260* (53)	*233* (42)
20.1-25^{o}C	*315* (56)	*49* (10)	*229* (41)
>25^{o}C	*67* (12)	*1* (0.2)	*47* (8)

Mean averaged floor joist moisture content ranged from 16.6-19.2% while mean ceiling joist moisture content ranged from 10.6-11.9% (Table 5.2). Mould was found infrequently in the 2005 survey (7% of houses with mould in the whole house and 4% of houses with mould in living and/or bedrooms) compared to the proportion of homes affected in 2010 (21% and 15%, respectively) and 2015 (46% and 18%, respectively). Musty odour was present in 11% of homes in 2010 and 6% in 2015. The prevalence of subjective dampness ranged from 11% in the 2005, 26% in the 2010, and 15% in the 2015 survey (Table 5.2).

Table 5.2. Moisture and mould assessments in three New Zealand house condition surveys

	2005 *565 houses* N(%)	**2010** *491 houses* N(%)	**2015** *560 houses* N(%)
Ceiling joist moisture			
Measurements obtained	482 (85)	376 (77)	422 (75)
Percent moisture content (Mean ± SD)	10.8 ± 1.7	11.9 ± 3.3	10.6 ± 5.1
Average floor joist moisture			
Measurements obtained	326 (58)	286 (58)	323 (58)
Percent moisture content (Mean ± SD)	19.2 ± 4.4	16.5 ± 2.7	16.6 ± 3.4
Mould in whole house	**N(%)**	**N(%)**	**N(%)**
Measurements obtained	565 (100)	491 (100)	560 (100)
Any mould	39 (7)	101 (21)	258 (46)
None	526 (93)	390 (79)	302 (54)
Specks	26 (5)	52 (12)	144 (26)
Patches	8 (1)	32 (6)	76 (14)
Large patches	2 (0.5)	13 (2)	30 (5)
Extensive	3 (0.5)	4(1)	8 (1)
Mould in living & bedrooms			
Measurements obtained	565 (100)	491 (100)	560 (100)
Any mould	22 (4)	72 (15)	102 (18)
Severity of mould			
None	544 (96)	419 (85)	458 (82)
Specks	11 (2)	31 (6)	42 (8)
Patches	6 (1)	24 (5)	38 (7)
Large patches	1 (0.5)	13 (3)	16 (3)
Extensive	3 (0.5)	4 (1)	6 (1)
Subjective damp			
Measurements obtained	565 (100)	348 (71)	539 (96)
Any dampness	63 (11)	91 (26)	80 (15)
Severity of dampness			
Dry	502 (88)	257 (74)	459 (85)
A little damp	54 (10)	50 (14)	53 (10)
Damp throughout	9 (2)	41 (12)	27 (5)
Musty odour (whole house)			
Measurements obtained	0	491 (100)	560 (100)
Odour present	-	52 (11)	36 (6)

5.3.1 Associations with ceiling and floor joist moisture

Linear regression of ceiling and floor joist moisture with mould severity did not show significant associations, except for specks of mould only, which was significantly associated with more floor joist moisture in the 2010 survey. Neither were any dose-response patterns evident (Tables 5.3a and 5.3b).

5.3.2 Associations with subjectively assessed dampness and musty odour

We found strong associations between the severity of mould and subjectively assessed indoor dampness, with clear dose-response trends (p<0.001 for all but one analysis), particularly when using the 2005 and 2015 survey data (Table 5.4). Analyses adjusted for roof and floor joist moisture measurements, and analyses excluding floor joist measurements, did not appreciably change the ORs, which were generally high, particularly for homes with patches or large patches/extensive mould, with some estimates indicating that mould is >20 times more likely to be reported when the house is also reported to be damp (Table 5.4). Consistent with these strong associations, mould explained a larger proportion of variance in indoor dampness (10-17%; Table 5.4).

Table 5.3 Linear regression of moisture measurements and visible mould severity

	2005			**2010**			**2015**		
				Ceiling joist moisture					
		N=482			N=376			N=422	
		R^2=0.002			R^2=0.007			R^2=0.002	
Visible mould severity	*n*	*Coef.*	*95% CI*	*n*	*Coef.*	*95% CI*	*n*	*Coef.*	*95% CI*
None	*448*	*(ref)*		*296*	*(ref)*		*227*	*(ref)*	
Specks	*23*	-0.02	(-0.74, 0.69)	*42*	0.60	(-0.48, 1.67)	*111*	0.46	(-0.71, 1.64)
Patches (or greater 2005 only)	*11*	0.51	(-0.5, 1.52)	*25*	0.84	(-0.52, 2.21)	*55*	0.40	(-1.12, 1.92)
Large patches/extensive (2010, 2015 only)				*13*	0.25	(-1.60, 2.11)	*29*	0.39	(-1.61, 2.39)
Trend		NS			NS			NS	
				Floor joist moisture					
		N=326			N=286			N=323	
		R^2=0.001			R^2=0.02			R^2=0.008	
Visible mould severity	*n*	*Coef.*	*95% CI*	*n*	*Coef.*	*95% CI*	*n*	*Coef.*	*95% CI*
None	*299*	*(ref)*		*214*	*(ref)*		*153*	*(ref)*	
Specks	*20*	-0.54	(-2.57, 1.48)	*35*	**1.14**	**(0.17, 2.11)***	*96*	0.04	(-0.82, 0.90)
Patches	*7*	-0.06	(-3.42, 3.29)	*23*	0.07	(-1.10, 1.24)	*44*	0.28	(-0.85, 1.42)
Large patches/extensive (2010, 2015 only)				*14*	0.69	(-0.78, 2.16)	*30*	1.00	(-0.32, 2.33)
Trend		NS			NS			NS	

N=number in group; n=number in subgroup; R^2=explained variance, 95%CI =95% confidence intervals, coef =coefficient, NS Non-significant

Both roof and floor joist moisture were independently associated with indoor dampness, with the odds of the house being subjectively characterised as damp increasing by approximately 10-30% with each increase of one percent moisture content. The explained variance was smaller than that observed for mould (Table 5.4).

Associations with musty odour showed very similar patterns, with significant dose-dependent relationships observed for the 2015 survey (Table 5.5). The percentage of explained variance was also similar (15-21%; Table 5.5), which was mostly accounted for by the association with visible mould (10-17%; Table 5.5). Musty odour and severity of dampness were strongly associated, with an equally large proportion of variance (35% to 43%Table 5.5). Dampness severity was so strongly associated with musty odour that in multivariate analysis with moisture measurements it obscured the effect of these variables (data not shown), therefore multivariate results are presented here without dampness severity (Table 5.5).

Table 5.4. Logistic regression of dampness, unadjusted and adjusted for other dampness variables (2005 mould reduced to 3 subcategories)

	2005			**2010**			**2015**		
	N/n *OR(95%CI)*	*N/n* *aOR(95%CI)* n=286 p=0.0000 R^2=0.15	*N/n* *aOR(95%CI)* *no floor* n=482 p=0.0000 R^2=0.19	*N/n* *OR(95%CI)*	*N/n* *aOR(95%CI)* n=173 p=0.000 R^2=0.21	*N/n* *aOR(95%CI)* *no floor* n=267 p=0.000 R^2=0.15	*N/n* *OR(95%CI)*	*N/n* *aOR(95%CI)* n=252 p=0.0000 R^2=0.16	*N/n* *aOR(95%CI)* *no floor* n=404 p=0.0000 R^2=0.18
Mould: None	R^2=0.17 *526/39* *Ref*	*262/25* *Ref*	*448/29* *Ref*	R^2=0.10 *267/47* Ref	*125/30* *Ref*	*205/40* *Ref*	R^2=0.16 *293/14* *Ref*	*123/12* *Ref*	*219/12* *Ref*
Specks	*26/15* **17.0 (7.3, 39.6)** ***	18/9 **9.7 (3.5, 27.0)** ***	*23/12* **17.7 (6.9, 45.4)** ***	*42/26* **7.6 (3.8, 15.3)** ***	*23/17* **9.3 (3.0, 28.3)** ***	*34/22* **7.9 (3.4, 18.1)** ***	*140/29* **5.2 (27, 10.2)** ***	*78/22* **3.9 (1.7, 8.9)** **	*108/25* **5.6 (2.6, 12.1)** ***
Patches (and greater, 2005 only)	*13/9* **28.1 (8.2, 95.4)** ***	*6/5* **40.7 (4.5, 366.5)** ***	*11/7* **24.7 (6.6, 92.5)** ***	*25/11* **3.7 (1.6, 8.6)** **	*15/6* 2.1 (0.6, 7.2)	*18/7* 2.1 (0.7, 6.0)	*70/17* **6.4 (3.0 (13.7)** ***	*29/9* **5.1 (1.8, 14.5)** **	*50/15* **9.0 (3.7, 21.7)** ***
Large patches/ extensive				*14/7* **4.7 (1.6, 14.0)** **	*10/4* 3.2 (0.5, 19.1)	*10/4* 2.9 (0.7, 11.2)	*36/20* 24.9 (10.7, 58.2)	*22/9* **6.5 (2.2, 19.6)** ***	*27/12* **15.5 (5.7, 41.9)** ***
Trend analysis	(p<0.001)	(p<0.001)	(p<0.001)	(p<0.001)	(p=0.02)	(p=0.001)	(p<0.001)	(p<0.001)	(p<0.001)
roof joist moisture	R^2=0.03 *482/48* **1.3 (1.1, 1.6)** **	*284/37* 1.17 (0.9, 1.5)	*482/48* **1.3 (1.1, 1.6)** **	R^2=0.06 *194/73* **1.2 (1.1, 1.4)** ***	*116/57* **1.2 (1.0, 1.4)** **	*194/73* **1.2 (1.1, 1.4)** ***	R^2=0.04 *340/64* **1.1 (1.0, 1.2)** ***	*252/52* **1.2 (1.0, 1.3)** **	*404/64* **1.1 (1.1, 1.2)** ***
floor joist moisture	R^2=0.00 *277/49* 1.0 (0.9, 1.1)	*284/37* 1.0 (0.9, 1.1)		R^2=0.09 *194/73* **1.3 (1.2, 1.5)** ***	*116/57* **1.3 (1.1, 1.5)** ***		R^2=0.04 *248/62* **1.2 (1.1, 1.3)** ***	*252/52* **1.2 (1.0, 1.3)** **	

*N=number in subgroup; n=number in subgroup rated as damp; *P≤0.05, **p≤0.01, ***p≤0.001; R^2=explained variance*

Table 5.5 Logistic regression of musty odour, unadjusted and adjusted for other dampness variables

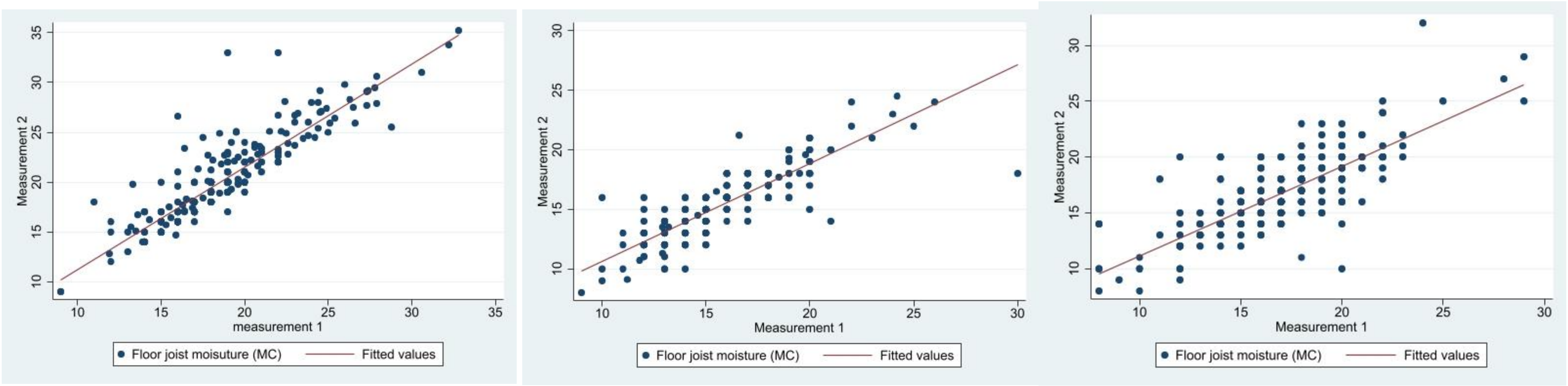
	2010			2015		
	N/n *OR(95%CI)*	*N/n* *aOR(95%CI)*	*N/n* *aOR(95%CI)* *no floor*	*N/n* *OR(95%CI)*	*N/n* *aOR(95%CI)*	*N/n* *aOR(95%CI)* *no floor*
		n=238 p=0.0000 R^2=0.20	n=376 p=0.0000 R^2=0.12		n=264 p=0.001 R^2=0.15	n=422 p=0.0000 R^2=0.15
Mould: None	R^2=0.10 *390/24* *Ref*	*176/14* *Ref*	*296/22* *Ref*	R^2=0.17 *299/3* *Ref*	*126/3* *Ref*	*227/3* Ref
Specks	*52/17* **7.4 (3.7, 15.1)** ***	*29/9* **4.4 (1.6, 12.3)** **	*42/14* **6.0 (2.7, 13.3)** ***	*132/12* **9.1 (2.5, 32.6)** ***	*81/8* **5.1 (1.3, 20.7)** *	*111/9* **6.6 (1.7, 25.0)** **
Patches	*32/7* **4.3 (1.7, 10.9)** **	*20/5* **3.9 (1.1, 13.9)** *	*25/5* *2.9 (1.0, 8.6)* *^*	*66/10* **15.0 (4.0, 56.4)** ***	*33/7* **12.5 (2.9, 55)** ***	*55/9* **14.6 (3.8, 56.8)** ***
Large patches/ extensive	*17/4* **4.7 (1.4,15.5)** **	*13/2* 1.8 (0.3, 10.6)	*13/2* 2.3 (0.5, 11.1)	*27/11* **40.6 (10.7, 154.4)** ***	*24/4* **8.5 (1.7, 42.3)** **	*29/6* **19.9 (4.6, 85.8)** ***
Trend analysis	(p<0.001)	NS	NS	(p<0.001)	(p=0.001)	(p<0.001)
Damp: none	R^2=0.35 *7/257* *Ref*			R^2=0.43 *4/459* *Ref*		
A little	*18/50* **20.1 (7.8, 51.8)** ***			*13/53* **37 (11.5, 118.7)** ***		
Damp throughout	*24/41* **50.4 (19.0, 133.6)** ***			*16/27* **165.5 (47.5, 576.5)** ***		
Trend analysis	(p<0.001)			(p<0.001)		
Roof joist moisture	*333/43* **1.2 (1.1, 1.3)** **	*238/30* **1.3 (1.1, 1.5)** **	*333/43* **1.2 (1.0, 1.3)** **	*395/27* **1.1 (1.0, 1.1)** *	*264/22* 1.0 (1.0, 1.1)	*422/27* 1.1 (1.0, 1.1)
Floor joist moisture	R^2=0.08 *333/43* **1.3 (1.2, 1.5)** ***	*238/30* **1.3 (1.1, 1.5)** **		R^2=0.05 *296/27* **1.2 (1.1, 1.4)** **	*264/22* **1.2 (1.0, 1.4)** *	

*N=number in subgroup; n=number in subgroup rated as damp; *P≤0.05, **p≤0.01, ***p≤0.001; R^2=explained variance*

5.3.3 Associations between floor and ceiling joist moisture measurements

Correlations between two moisture measurements taken from floor joists >5m apart were moderately to highly correlated (Figure 5.1). Associations between the ceiling and floor joist moisture measurements differed by survey with the 2005 survey (undertaken in summer) showing the strongest association (Figure 5.2a) correlation for 2005 = 0.3, vs 0.15 for 2010 and 0.18 for 2015 (data not shown in table or figures). Stratified analyses by climate zone showed similar associations, but consistently lower floor joist moisture was found in the Southern climate zone (Figure 5.2b; presented for all three surveys combined).

Figure 5.1. Scatterplot of two moisture measurements from floor joists 5m apart, with regression line fitted



2005

2010

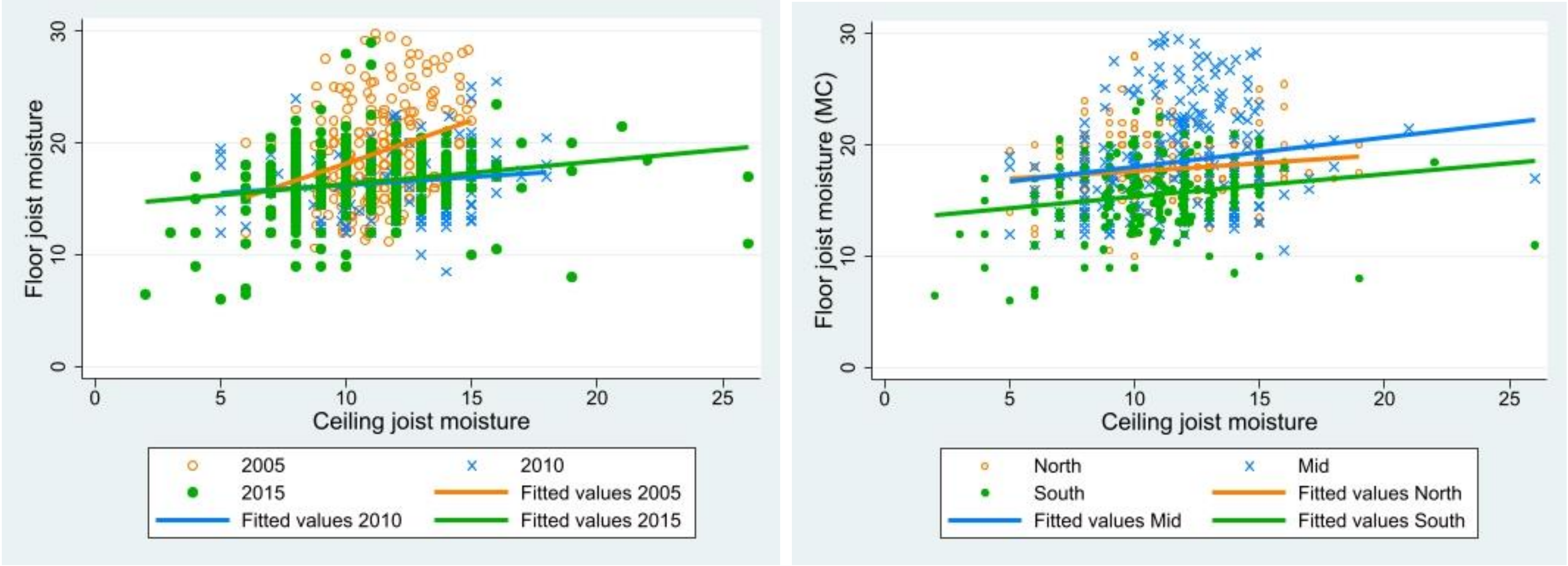
2015

Corellation = 0.64 p<0.01 (n=258)

Corellation = 0.85 p<0.01 (n=259)

Corellation = 0.79 p<0.01 (n=323)

Figure 5.2. Relationship between averaged floor joist and ceiling joist moisture, by survey and climate zone



(a) (b)

5.4 Discussion

This study showed that observations of indoor mould severity were associated, in a dose-dependent manner, with subjective dampness and musty odour. Floor and ceiling joist moisture measurements were not associated with mould severity, but were significantly associated with both subjective indoor dampness and musty odour separately. Subjective indoor dampness and musty odour were the two dampness measurements most strongly associated. While ceiling joist moisture and floor joist moisture measurements taken from the same house were moderately to highly correlated with each other, the effect size of one to the other was small, except for in 2005, the survey conducted in summer where the least dampness and mould was found.

5.4.1 Consistency across surveys

Floor joist moisture was, on average, highest in 2005 (Figure 5.2a; see also below). In contrast, ceiling joist moisture was higher, and subjective dampness and musty odour more prevalent in 2010, whilst mould was most prevalent in 2015 (Table 5.2, Figure 5.2). This lack of agreement in terms of which sample had most “dampness” overall, combined with relatively modest correlation between various indoor dampness indicators (discussed below) suggests that these measures may represent different aspects of indoor dampness. On the other hand, differences between surveys may also have played a role. In particular, when expressed for the whole house, mould was found approximately twice as frequently in 2015 compared to 2010, while the proportions were more similar (but still higher) when restricted to mould in living and bedrooms. This suggests that in the 2015 survey more attention was paid to observations of mould in other parts of the house. Personal communications with the survey designers confirmed that this was indeed the case, driven by increased awareness of indoor mould related adverse health effects. Also, the 2015 survey included rental housing, which we have previously shown to be associated with more indoor mould [18]. So, the lack of consistency in quantifying indoor dampness when applying different measures across multiple surveys is likely due to a combination of changes in assessment criteria between surveys and different measures representing different aspects of indoor dampness.

These findings highlight the potential limitations of subjective dampness indicators including visible mould, which, despite some quantitative criteria (size/extent), may not be comparable across studies, or even within studies, when performed by different inspectors. Nonetheless, they are often most consistently associated with moisture measurements [19], and with adverse health effects [3, 20]. Therefore, despite the difficulty in standardising these assessments, they remain important. However, further work to reduce subjectivity and increase consistency between and within studies is needed.

Objective measurements of ceiling and averaged floor joist moisture content were relatively consistent across the three surveys, with the exception of floor joist moisture measured in 2005, which was higher than that measured in the other surveys (2005: Mean 19.2%, SD 4.4% versus Mean 16.5%, SD 2.7% and Mean 16.6%, SD 3.4% in 2010 and 2015, respectively; Table5. 2). Interestingly, in 2005 we also found a stronger association between floor and ceiling joist moisture (2005 $r = 0.30$, vs 2010 $r = 0.15$, and 2015 $r = 0.18$; Figure 5.2a). Annual climate reports for New Zealand described the period these measurements were taken (late Dec 2004 to August 2005) as generally warmer than average with higher rainfall in the North and Mid climate zones and lower rainfall than average in the Southern zone, [21] which may have contributed to the higher moisture levels observed in floor joists in 2005. This would be consistent with a large European multi-centre survey that found that houses in centres with higher average annual rainfall and temperature were more likely to be damp and mouldy [22]. Analyses reported in Chapters 3 and 4 were adjusted for 30-day maximum temperature and total rainfall data obtained from weather stations across New Zealand. Although regression coefficients were not presented, no clear association between 30-day weather station information and ceiling and floor joist measurements were found; using smaller increments including 3 days, 7 days, 14 days and 21 days did not change this (data not shown). It therefore remains unclear why floor joist moisture measurements were higher in 2005 and why for the 2005 survey there was a stronger association with ceiling joist moisture measurements.

5.4.2 Interrelationships between subjective dampness measures

5.4.2.1 Dampness and visible mould

Positive and consistent associations between visible signs of mould and subjective indoor dampness were observed, including dose-response associations for mould severity across all three surveys. Despite the apparent strength of this association, it cannot be discounted that this may be due to inspectors being more likely to assess a house as damp if they also observe visible mould.

Although other studies have used different definitions of dampness, generally based on observations of damp spots on walls and floors, we consider that comparisons with these studies are useful, particularly as there is no universally agreed definition of indoor dampness. Several other studies, conducted in the UK, report similarly strong or even stronger associations between visible mould and indoor dampness, including a study that reported that 97% of houses with evidence of dampness identified by inspectors also had visible mould [23]. Martin et al., found that 70% of damp dwellings also had visible mould, again with both assessments conducted by inspectors [24], and Williams et al., reported that 86% of houses with self-reported visible mould were also reported as damp (r 0.51; p<0.001) [25]. Another study, like ours conducted in New Zealand, found weaker links, with a correlation coefficient of only 0.11 (p≤0.05) for the most extreme level of (inspector assessed) feeling of dampness ("very damp") and (inspector assessed) visible mould, and no significant correlation between visible mould and observations characterised as "a little damp" [26].

5.4.2.2 Odour, dampness and mould

In our study, inspector assessed subjective dampness and musty odour were the most strongly associated dampness indicators, with explained variance of 35-0.43% in univariate regression. No other studies have reported on the relationship between inspector/researcher assessed mouldy or musty odours and other dampness indicators or moisture measurements. However, several studies reported associations between participant-reported mould and musty odour. One of these, consistent with our results, reported that the presence of mouldy odour was significantly associated with (self-reported) visible mould in one of four centres (in the other three the association was positive, but results were not statistically significant), and with observed water damage, also in one of four centres [27]. A study using participant-reported dampness (condensation, high humidity in the bathroom, history of leaks) and several different odours (musty, mouldy, stuffy and pungent) found that 31% of houses with any sign of dampness had a "musty odour", while 6% had "mouldy odour", and 53% had any one of the considered odours, compared to only 26% of those houses without other signs of dampness [14]. Another study reported a correlation coefficient of 0.26 (non-significant) between self-reported visible damp spots and mouldy odour [34]. A fourth study, using participant-reported dampness and odours, reported an odds ratios of 5.46 ($p \leq 0.001$) for the likelihood of mouldy odour being reported in homes also reported to be damp. And in a fifth study, mouldy odour was also strongly associated with participant-reported floor moisture (OR 4.38; $p \leq 0.001$) [28]. No studies were found with results inconsistent to those reported in our study.

5.4.3 Moisture measurements

Correlations between ceiling and average floor joist measurements were significant but relatively low, with the highest correlation coefficient being 0.29 ($p < 0.001$) in the 2005 survey. Since the timber framing of a house is a continuous enclosed space, a higher degree of correlation between floor and ceiling joist measurements might be expected. In our earlier paper [18], using the same data, we showed that floor joist moisture measurements, but not ceiling joist measurements, were associated with the building envelope condition (BEC), as well as conditions in the subfloor, including ponding of water or leaks, presence of a ground vapour barrier and adequate subfloor ventilation [29]. This suggests that floor and ceiling moisture measurements may provide distinct proxies of indoor dampness, explained by different house characteristics.

The relationship between two moisture measurements taken from floor joists more than five metres apart were moderate-to-highly correlated (Figure 5.1), demonstrating some intra-house variability in moisture within a specific zone (subfloor space). This may be due to localised moisture sources, such as leaks. Multiple measurements from the same specific zone may therefore reduce some measurement error, which could be effective, particularly if multiple measurements can be taken without much effort.

No other studies were identified that report associations between two or more objective moisture measurements in surveys of occupied homes (some studies took multiple objective measurements, but these were aggregated or summarised for reporting). A review paper assessing the utility of such assessments for use in studies on health effects, found that measurements of moisture in materials (i.e. moisture content in wallboard or skirtings) showed stronger associations with health effects than both subjective measures such as visible mould and signs of dampness and other objective measurements such as relative humidity (of indoor air), or mould spores and fragments [30]. Nonetheless, measures of moisture content remain uncommon in epidemiological studies. This is probably due to a lack of a standardised methodology, with no widely accepted consensus on where, and from what materials, measurements should be taken. Other issues such as potential damage (from the pins in the meters), calibration and repeatability can more easily be resolved. In our study, measurements were taken from the timber framing, thus not resulting in any damage to internal surfaces. It is also more likely to provide an indication of the state of the (house) structure, independent of the internal conditions, although this could not be confirmed. Pairing measurements obtained from timber framing with measurements from internal surfaces (e.g. skirting boards) may provide a more complete measure of indoor dampness, although, again, this could not be established from the current study.

5.4.4 Relationships between objective and subjective measures of dampness

Both floor and ceiling joist moisture were significantly associated (inspector assessed) indoor subjective dampness and musty odour, while not being associated with visible mould. As discussed previously, with a single inspector responsible for both the objective and subjective assessments, it is possible that bias may account for at least some of this association. Nevertheless, it is an interesting and unexpected finding that may point to important differences between the various subjective dampness indicators. Of note is that subjective (sensation of) dampness and musty odours are aspects of indoor air quality, while visible mould is an aspect of indoor surfaces. The relationship between surface moisture and indoor air moisture is worth further consideration.

Several other studies compared objective and subjective measures of indoor dampness. Macher et al measured water moisture equivalent (WME), using a pinless protimeter, on non-timber materials (gypsum wall-board, 45-60cm above floor level, on the internal face of all external walls and on walls immediately adjacent to bathrooms, kitchens and laundries) and found a significant association between maximum living room measurements and musty odour [31]. They also reported that the presence of more cumulative dampness indicators were related with higher average living room and bedroom wall WME [31]. Unfortunately, in our study, due to the high frequency of missing data resulting in less than half the sample not having data on all five dampness measurements, we were not able to do similar analyses. Another study assessed the association between "detectable dampness", measured using an almost identical instrument (protimeter) as in our study, but on interior walls just above floor level, and indoor visible mould. Correlations were calculated using a severity scale for each variable, resulting in a positive association, unlike our study, with a reported correlation coefficient of 0.51 ($p \leq 0.05$) [25]. In another study, Dales et al also reported a correlation between relative humidity (RH) indoors and (visible) mould surface-area (MSA) of 0.21 ($p < 0.001$) [32]. In contrast, a study looking at bias in self-reported dampness assessments using measurements from internal wall surfaces, found that "the majority of homes with high surface wall moisture had no *(self-reported)* visible mould" [33]. Better understanding of the relationship between floor (and ceiling) joist moisture and indoor surface (e.g. wall) moisture would be of value.

5.4.5 Strengths and weaknesses

A strength of this study is that multiple measures of dampness were included, both objective and subjective, and that we were able to make comparisons for consistency between multiple iterations of the same survey. The study also has weaknesses. Firstly, a significant amount of missing data (for the objective measurements typically due to a lack of roof space accessibility and/or concrete slab foundations) reduced the strength of our analyses, and precluded analyses involving cumulative assessments of dampness outcomes (discussed above). Secondly, the measurement protocols for visible mould differed between the three surveys. This means that where we see differences between surveys, it is not possible to know if these are due to methodological differences or to other external factors. Another weakness is the important differences in the three survey samples in terms of tenure and condition (discussed in more detail in previous chapters), as well as season of survey observations. These differences further reduce the comparability of the three iterations of the survey. Our study used inspector-assessed dampness measurements, thus providing a single observation in time, which may not accurately reflect the situation throughout the year. As noted above, subjective measurements of dampness and musty odour were conducted by the same inspector assessing visible mould, and observations of high levels of visible mould, or high moisture measurements, may “prime” an inspector to expect dampness and musty odour, so the three measures cannot be considered entirely independent of each other. Another weakness is that with no health data collected, we were not able to assess which of these measurements may relate most strongly to health effects. Finally, as there are no gold standards for any of the measured indoor dampness indicators it remains unclear whether differences in associations between objective/subjective assessments, namely the fact that objective assessments were associated with subjective dampness and musty odour, but not with visible mould, are due to (different levels of) measurement error across measures, or that perhaps these are actually measuring different types or aspects of dampness.

5.5 Conclusions

In conclusion, objective measurements of framing moisture were associated with subjectively assessed indoor dampness and musty odour but not with visible mould. Furthermore, multiple objective measurements from the same house were only moderately associated. Together, this evidence suggests that any single measure by itself may not validly quantify the full extent of indoor dampness. Therefore, to reduce exposure misclassification in epidemiological studies, indoor dampness may be best captured by using multiple measures, at least until more information is available about which of these measures are most strongly associated with adverse health outcomes.

5.6 References

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6 General discussion

6.1 Introduction

This thesis is based on three New Zealand House Condition Surveys, conducted in 2005, 2010 and 2015, and assessed associations between five dampness related outcomes (subjective indoor dampness, indoor visible mould, musty odour, floor and ceiling joist moisture measurements) and house characteristics and condition; it also assessed associations among the various dampness measurements. Over the past thirty years, many epidemiological studies have assessed associations between house characteristics and indoor dampness, seeking to improve the understanding of the causes of house dampness (with the aim of developing effective interventions), and their impact on occupants' health. This thesis aimed to build on this work, with a particular focus on the association between house characteristics (at a relatively fine-grained level) and the five dampness measurements recorded in the surveys. The surveys assessed in this thesis do not include health assessments, but this work remains of interest primarily to facilitate the development of interventions to reduce indoor dampness-related harm to occupants. The main findings of this research are identified below, followed by a discussion of specific results, the strengths and weaknesses of the research, recommendations for future work, and overall conclusions.

6.2 Main findings

- Poorer condition of the building envelope (roof, wall claddings, windows, paint and spouting and guttering) was independently associated with more visible mould (in living and bedrooms), musty odour (Aims 2 & 4, Chapter 3) and subjective indoor dampness (Aim 2 & 4, Chapter 4). It was also associated with higher measured moisture in floor, but not ceiling joists (Aims 2 & 4, Chapter 4)

- More extract ventilation (presence of kitchen, bathroom and clothes dryer extraction), was independently associated with less visible mould (in the living and bedrooms), musty odour (Aims 1 & 4, Chapter 3), and subjective indoor dampness (Aims 1 & 4, Chapter 4)

- More insulation (presence in ceiling-space, underfloor and wall cavity) was independently associated with less visible mould (in the living and bedrooms), musty odour (Aim 4, Chapter 3), and subjective dampness.

- More insulation, and more ventilation were not associated with moisture measured in ceilings and floors (Aims 1 & 4, Chapter 4).

- Poorer conditions in the subfloor area (lack of ventilation, evidence of ponding or leaks, absence of ground vapour barrier (ground cover)) were independently associated with more musty odour subjective indoor dampness (Aims 2 & 4, Chapter 4), and higher moisture content in subfloor framing timbers (floor joists) (Aims 2 & 4, Chapter 4) Subfloor conditions were only associated with visible mould only in the whole house (in 2010 only), but not with visible mould if restricted only to that found in the living and bedrooms (Aims 2 & 4, chapter 3)

- Associations restricted to visible mould in living and bedrooms were similar to those reported for visible mould in the whole house, although effect sizes were generally somewhat smaller (Aim 5, Chapter 3).

- Indoor visible mould was significantly less likely in the southern-most (coldest) climate zone, when adjusted for other house characteristics described above (Aim 7, Chapter 3).

- Fibre-cement wall cladding (when compared with timber cladding) was independently associated with more subjective dampness and musty odour (Aim 1, Chapters 3 & 4).

- The absence of a ground vapour barrier and the presence of ponding or leaks under the house were associated with greater moisture content in subfloor framing timbers (floor joists) (Aim 2, Chapter 4).

- Older houses and houses with concrete or clay roof tiles (versus metal roof cladding) were independently associated with higher ceiling joist moisture content (Aim 1, Chapter 4).

- Extent of visible mould (on a scale from None; specks; patches; Large patches; Extensive) was associated in a dose-dependent fashion with both subjective indoor dampness and presence of a musty odour (Aim 6, Chapter 5).

- Increased subjective indoor dampness and musty odour were both associated with higher measured moisture content in floor and ceiling joists (Aim 6, Chapter 5).

- Indoor visible mould, assessed by inspectors, was not associated with moisture measurements in ceiling and floor joist timbers (Aim 6, Chapter 5).

6.3 Discussion of specific results

In the following sections several specific findings are selected for further discussion. Rather than repeat topics already covered in the discussion sections in each of the chapters describing the results of this thesis (Chapters 3, 4 and 5), here the aim is to synthesise previously discussed findings and focus on those most generalisable or those that are most important.

6.3.1 House Characteristics

6.3.1.1 Insulation and Ventilation

Several previous studies have considered ventilation, including whether certain types of system are more effective in reducing dampness and mould than others (Chapter 2, section 2,12). Although increased ventilation (or air-change rate) is generally associated with reductions in dampness and mould in the literature, there were two notable issues identified in Chapter 2. Firstly, the more highly-engineered systems do not appear to be significantly better than those that rely on simpler technology. For example, extract only kitchen and bathroom fans and even increased use of open windows for ventilation were similarly effective compared to balanced ventilation systems (with controlled supply and extract air). Studies described in this thesis did not include any information on ventilation behaviours, hence our examination was restricted to just presence or absence of ventilation components. A small proportion of houses (5-10 houses in each survey) had specialised ventilation systems, (HRV and DVS), which are similar heat recovery ventilation systems that use the warm air inside roof spaces to provide air conditioning of room air. The analyses described in this thesis (Chapters 3 and 4) showed that these systems were not associated with both indoor dampness indicators and timber moisture measurements. On the other hand, presence of bathroom and kitchen extract ventilation was consistently associated with reductions of all three indoor dampness indicators (Chapters 3 and 4), but they were not associated with moisture measurements (Chapter 4). Both of these findings are consistent with other reported results [1-4]. One important question for consideration in exposure assessment of dampness and mould is whether ventilation systems were installed in response to dampness issues, which anecdotal evidence suggests may often be the case in New Zealand with the systems described above. In this case, reverse causality may mask any beneficial effects (in terms of indoor dampness and mould) of these ventilation systems.

A second issue identified in chapter 2, was that evidence that better ventilation reduces exposure to musty or mouldy odours in the literature is weak, and suggestive of a lack of association. In the studies described in this thesis, extract ventilation was highly protective of musty odour (see Tables 3.3 and 3.4, Chapter 3) which was assessed by an inspector. As musty and mouldy odours have been strongly linked in the literature to harmful health effects, this is a useful finding.

Insulation has also been a focus of many previous studies evaluating indoor dampness, as described in Chapter 2. In the research undertaken as part of this thesis, less insulation in homes was associated with more indoor dampness, mould and musty odour (Table 3.4, Chapter 3; Table 4.3, Chapter 4). In the literature, insulation was also lacking strong evidence of an impact on musty and mouldy odours (See Chapter 2, section 2.11). In these results, each of the three insulation variables included in the insulation domain (ceiling, underfloor and wall cavity) were not consistently associated with musty or mouldy odour in univariate analyses (See Chapter 3, Table 3.3), and as result, were therefore not included in the multivariate analyses. However, when considered cumulatively, these three types of insulation were associated with significantly less musty odour (see Table 3.4, Chapter 3), although this was only evident in 2010, the survey that included the largest proportion of survey visits conducted during the colder seasons. If a larger proportion of survey visits across all surveys had been conducted during the colder seasons, the effect of insulation on indoor dampness indicators may have been more pronounced.

6.3.1.2 Occupancy and Tenure

Higher occupancy and renting, as opposed to owner occupied status, were two other previously reported associations for which results were in agreement with the international literature. In particular, the studies described in the thesis showed that high occupancy and rental status were independently associated with more indoor dampness, mould and musty odour (Table 3.4, Chapter 3; Table 4.2, Chapter 4). As was also shown in the literature (Chapter 2, section 2.12) increased occupancy was consistently associated with more subjective dampness and visible mould indoors. However, occupancy was not associated with musty odour or with measured floor and ceiling joist moisture; the reasons for this are unclear.

The association between rental tenure and indoor dampness was able to some extent to be disambiguated from likely confounders (variables known to differ by tenure, which are also related to indoor dampness). In particular, higher occupancy rates in, and poorer condition of rental houses (both of which have also been reported elsewhere [5, 6], together with insulation and ventilation characteristics, were unable to fully explain worse dampness in rental houses (included only in 2010 and 2015). An independent association between increased indoor dampness and rental tenure remained after adjusting for these factors, across all three of our indoor dampness measures (subjective dampness, mould and musty odour). It was these differences in the inclusion of tenants which was one of the primary deciding factors in analysing the three surveys separately, and in this way we can be confident that the persisting associations with rental tenure are not caused by differences in survey method, but that there are unexplained differences remaining after accounting for all the covariates in the multivariate analysis. It is likely that behaviours may also differ by tenure status, in particular heating behaviours (due to differences in socioeconomic status). Future studies on the determinants of indoor dampness, if they included detailed information on heating and ventilation behaviour, as well as other house characteristics consistently associated here, may more fully explain the reasons for the association between rental tenure and indoor dampness.

6.3.1.3 Domains of house characteristics

The analysis method used in this thesis involved measuring associations between individual house characteristics and several indoor dampness indicators and moisture measurements. This was followed by analyses assessing associations with house characteristics grouped into specific domains. The domains included insulation (insulation in three different cavities; ceiling, wall and floor), ventilation (extraction vents or fans in three different wet areas; kitchen, bathroom and clothes dryer), subfloor (three subfloor defects; ponding or leaks, insufficient subfloor ventilation (openings) and absence of a ground vapour barrier) and building envelope condition (BEC) described in more detail below in section 6.3.1.4. The selection of house characteristics for each of these domains was informed by the earlier multivariate analysis (for more detail on these methods see appendices 1 and 2)

This method showed that associations were more clearly observed when individual characteristics were grouped by domain and summed to tests dose-response associations (Chapters 3 and 4). Houses with a higher cumulative score within these domains, consistently had stronger associations with dampness indicators, although only the building envelope and subfloor domains were associated with moisture measurements. For example, while bathroom ventilation, which was one of the more consistently associated individual components, was associated with similar effects sizes for reduced likelihood of each of the indoor dampness indicators, (across the three indicators and three surveys), many of these independent results were not statistically significant in multivariate analysis. When summed within the ventilation domain, the three types (see above) were associated with statistically significant effects in six of the seven outcomes/surveys analysed for this (ventilation) domain, and furthermore, all six of these were also associated with statistically significant dose-response trends (Table 3.4, chapter 3, Table 4.3, chapter 4). Similar increases in strength of the associations were seen in each of the domains.

These results suggest that the individual components within each domain may contribute in an additive way. The individual house characteristics included within the domains identified here could easily and routinely be collected in epidemiological studies; if they were, this may lead to improved understanding of the association between house characteristics, dampness and potentially health effects (although the latter could not be established in the current thesis as no information on health was collected).

6.3.1.4 House condition

This study examined the influence of the condition of specific building envelope characteristics, independently and cumulatively, with the latter referred to as the building envelope condition (BEC) domain. The house characteristics included the condition of the roof, wall cladding, windows, spouting and guttering, and exterior paint, all rated by trained inspectors. As also noted above, the approach of assessing individual characteristics resulted in only few consistent associations with indoor dampness indicators or framing moisture measurements in multivariate analyses (although, poorer overall window condition came close to being consistently associated across surveys with all three indoor dampness indicators, although this was not always statistically significant). However, when assessed cumulatively (as the BEC domain), associations with indoor dampness indicators (dampness, mould, musty odour, floor joist moisture) were very consistent, and highly statistically significant dose-response trends were observed (Table 4.4, chapter 4; Table 4.3, chapter 4; Table 4.6, Chapter 4). Furthermore, associations were independent of the ventilation and insulation domain, as well as occupancy, tenure and climate zone.

These results suggest that building envelope condition is an important determinant of indoor dampness and mould.

The use of an overall house condition rating (assessed as: well maintained; reasonably maintained, and poorly maintained), was assessed in this thesis, and this was also associated with indoor dampness and mould, with also some evidence of an association with moisture measurements. It is notable that while the indoor dampness indicators were generally more strongly associated with this maintenance rating than with the BEC variable, both floor and ceiling joist moisture were more strongly associated with the BEC variable. This may be due to inspections of mould indoors contributing to the overall maintenance rating. Furthermore, an overall rating may be more prone to bias as the scoring may be influenced by age of the house and socioeconomic status, rather than factors directly related to house condition. These factors may make this overall rating less useful for assessing associations with indoor dampness. On the other hand, by assessing the condition of specific components of the building envelope, the relationship is restricted more specifically to factors that can be expected to have a causal relationship with indoor dampness, while avoiding confounding by inspector bias, who may be primed to notice more mould and dampness in generally poorer condition homes. Furthermore, as discussed in Chapters 3 and 4, visible mould may often be considered to be an aspect of poorer condition (as it is also in moisture transport modelling), and therefore should not also be assessed as an outcome, as this could produce inflated effect estimates. This is consistent with our finding that associations with this variable were more strongly associated with indoor dampness than the BEC variable.

While this finding is based on cross-sectional data, and therefore cannot prove causality, the observed dose-response associations with building condition (with poorer building condition associated with more indoor dampness issues) suggest that associations may be causal. If true, this is likely due to houses with poor building envelope condition being more prone to increases in leakages and have reduced effectiveness to both keep water out of the structure, and to channel it away from the house (in the case of spouting and guttering).

6.3.2 Dampness measurements and indicators

In epidemiological studies, indoor dampness is often used, separately from other dampness indicators such as visible mould and musty or mouldy odour. It is often assessed using visual cues such as damp patches or stains or evidence of past water damage on walls or floors (see Chapter 2). The New Zealand House Condition Surveys, on the other hand, used an entirely subjective assessment, based on a feeling, perception or sensation of dampness, and was rated on a three-point scale: dry; some dampness; damp throughout. A subjective assessment is also used for the presence of a musty or mouldy odour anywhere in the house (Yes/No). These two assessments, while both highly subjective, showed the strongest associations with both visible mould and with objective moisture measurements (Table 5.3, Chapter 5). Furthermore, associations with house characteristics, explored in Chapters 3 and 4, were strongly associated with subjective dampness and musty odour, as well as with mould in the whole house. This suggests that doing away with, or replacing, subjective assessments with more objective measures may not necessarily result in clearer associations and improved understanding of main drivers of indoor dampness. Instead, attention to standardising protocols for collection of such subjective measures may be a better way to move towards improved understanding of indoor dampness.

This is an important finding from an epidemiological perspective, as studies have shown that the presence of a musty or mouldy odour, which could be considered the indicator most prone to bias and subjectivity, is a dampness indicator that is strongly and consistently associated with harmful health effects [7], including new-onset wheeze in infants [8]. Therefore, findings described in this thesis support the idea that it should remain a focus of studies of indoor dampness, and work to improve standardisation of this assessment is therefore of value.

In Chapter 5, it was shown that the various dampness assessments used in the surveys were not very strongly associated to one another, which suggest they may each capture different aspects of dampness, and therefore studies which collect fewer dampness outcomes may not be fully accounting for indoor dampness. Furthermore, other additional measures may be useful for research aimed toward standardising dampness assessment protocols and defining house dampness.

6.3.2.1 Associations between framing moisture and indoor dampness

Houses in our study rated as having indoor dampness and musty odour, also had higher measured moisture in ceiling and floor joists (Table 5.3, Chapter 5); however, while presence of more insulation and ventilation, were associated with less indoor dampness, mould and musty odour, there was no parallel association with lower floor and ceiling joist moisture associated with these parameters. A similar situation was also observed with the number of occupants, with more subjective dampness and visible mould observed, but no association with moisture measurements. The contribution of moisture generated indoors (such as during cooking and washing) has generally been considered an important determinant of framing and cavity moisture, particularly in older buildings, constructed with low airtightness, and in climatic conditions typical in New Zealand [9, 10]. Therefore, it is surprising that we did not observe lower framing moisture in houses with better insulation and ventilation, or higher framing moisture with more occupants. Several reasons why this may be the case are possible. Firstly, our data lacks information on moisture in wall cavities, whereas most models of moisture transport focus primarily on wall cavities. Therefore, the primary causes of wall framing moisture may differ significantly from those affecting ceiling and floor joists. Our results indicate that ceiling and floor joist moisture may be strongly influenced by the stack effect. This is evidenced, for example, by the strong association between poorer subfloor conditions and indoor subjective dampness (see Table 3, Chapter 4), and this may have less influence on wall framing.

Secondly, it may be that our data is missing important information, particularly information on occupant behaviours including heating and ventilation behaviours. This reduces our ability to observe associations, although this seems less likely since these associations were clearly observed with indoor dampness indicators despite the missing information. Furthermore, the influence of externally derived moisture on floor joists due to poorer condition of the building envelope and subfloor were clearly observed in floor joist moisture levels. Perhaps instead, the contribution to cavity moisture from the indoor environment, on average, may be less than models [10] suggest.

Understanding the flow of moisture through structures is complex, and *ASHRAE Standard 160: Criteria for Moisture-Control Design Analysis in Buildings*, which is generally considered the authoritative text in this sphere, is acknowledged as a work in progress [11]. New Zealand scientists at BRANZ have been working on this issue over recent years, conducting experiments in tandem with moisture transport modelling in test houses [9]. The resulting models were poor at predicting humidity levels in the wall cavities, which was consistently far higher than predicted. The author noted that field measurements of wall humidity in real buildings would be invaluable for improving the understanding of these conditions [9].

6.3.2.2 Separating assessments of moisture in air and moisture held in surfaces.

Following on from the discussion in the previous section, one methodological change, which may help shed useful additional light on the associations highlighted here, is if dampness indicators were measured alongside both dampness in air (e.g., RH) and moisture measurements in materials, for example floor and ceiling joists, and also internal wall linings, floors or skirtings. Some of the evidence presented here (Chapters 2 - 5), when combined, may be pointing towards these two types of dampness exposure having different determinants. In particular, it may be that moisture in indoor air is typically driven by behaviours of occupants (moisture production (cooking, cleaning), and modification (heating and ventilation) behaviours), while moisture in surfaces may be more often driven by factors related to the external environment, mediated by condition factors, such as poorly maintained claddings and windows, missing ground vapour barriers, and a leaks or ponding water under the house.

The analyses described in this thesis appear to point towards visible mould perhaps being more closely related to moisture generated indoors, hence its strong associations with ventilation, insulation and occupancy, while musty odour might be more closely related to moisture held in materials and the structure itself, hence much stronger association with both poorer subfloor conditions and building envelope condition, compared to visible mould (see Chapter 3, table 3.4) and its relatively strong association with moisture measurements in floor and ceiling joists (Chapter 5, Table 5.3). Another result which appears to support this hypothesis is the fact that fibre-cement wall claddings were strongly associated with musty odour, but not with visible mould (see Table 3.3, Chapter 3). Fibre-cement claddings are known to be more moisture absorbent than other wall claddings [12], hence this might also point toward musty odour being related to moisture held in the structure of the building.

While there were noticeable differences in the determinants of visible mould and musty odour, as well as differences in their relationships to moisture measurements, subjective indoor dampness was in general associated with the determinants of moisture in both.

Perhaps suggesting an intermediary relationship. Other researchers have hypothesised that musty and mouldy odours may denote the presence of mould (whether visible or hidden inside wall cavities) in a more “active” phase [13]. The hypothesis laid out here by the author, would denote a somewhat modified version of this, where musty odour may denote moisture held in materials that is “actively” released into the indoor environment. In other words, the odour may designate that the water has been held in materials.

Of course, each indicator may be associated with both “types” of dampness (held in air or surfaces) but may be more strongly influenced by one or the other. This area is worthy of further research. Obviously, there is exchange of moisture from air to surfaces, and vice versa, however, it is the author’s contention that this relationship is not yet well understood. As discussed in Chapter 2, musty odour, an indicator that is commonly associated with harmful health effects [13], has been demonstrated to be more common in rental houses, and rental houses are commonly in need of more repairs. This suggests, indirectly, that there may be a link between poorly maintained external claddings, moisture in materials, and the presence of as musty odour. If true (this could not be fully addressed in the studies presented in this thesis) then that may provide a basis for effective interventions to reduce indoor dampness-related health effects.

6.3.2.3 Summary – dampness measurements and indicators

In summary, what our results suggest is that moisture penetrating from the exterior, as a result of poorer condition BEC, may increase both framing (floor joist) moisture and indoor dampness mould and musty odour, whereas other characteristics , such as insulation, ventilation occupancy and tenure, may affect only indoor dampness indicators and not floor or ceiling joist moisture. In particular, results presented here suggest that the beneficial influence of keeping the indoor environment warm and well ventilated (as indicated by optimal insulation and ventilation) may not be enough to fully excise the negative impact of a poorly maintained building envelope on indoor dampness and mould (Table 3.4, Chapter 3).

6.3.3 Influence of climate

The influence of climate on indoor dampness and mould was examined in our research using two different methods. Firstly, with the use of a climate zone variable, based on latitude (and which has been used in the New Zealand building code to specify insulation levels), which splits the country into three zones; North, Mid and South. Secondly, climate was considered by accessing weather data (daily high temperature and daily total rainfall) from the weather station closest to each house, for the 30 days up to and including the day of inspection.

The climate zone variable was consistently associated with visible mould (when considered anywhere in the house). Houses in the Southern, cooler climate zone had less indoor visible mould and the lowest average floor joist moisture (Fig 5.2, Chapter 5), while houses in the Northern zone had more visible mould (Chapter 3). While houses in the South often have thicker insulation in construction cavities (particularly the newer houses), these associations remained even after adjusting for the presence or absence of each type of insulation (ceiling, wall and underfloor) (Table 3.4, Chapter 3), meaning these differences in insulation thickness cannot fully explain the differences in mould occurrence between different climatic zones. Similar relationships have been demonstrated in other studies for visible mould [14], however, a finding in our study that this association only applied to visible mould, and neither musty odour or subjective indoor dampness, may be worth further exploration, especially in exploring the question whether visible mould is reflecting a somewhat different dampness issues as subjective dampness and musty odour.

The 30-day rain and daily maximum temperature were significantly associated with most of the dampness outcomes including visible mould, but associations were not consistent in direction of effect, and effect sizes were relatively small (Chapter 5). Another study from throughout Europe, assessing similar climate variables (average temperature and rainfall) in association with dampness and mould (combined into a single variable), reported that warmer annual average outdoor temperature was associated with a higher likelihood of dampness and mould indoors. This study used annual averages of rainfall and temperature of each region within the study, rather than temperature and rainfall immediately prior to the survey, and found that higher temperature and rainfall were both significantly associated with increases in indoor dampness and mould, independently of construction year and socio-economic status [14]. Their results are consistent with our finding of less floor moisture and visible mould in the Southern climate zone, which is both the coolest and driest of the three included climate zones, however our results did not replicate the consistent associations with temperature and rainfall data of Norback et al. There are numerous possible reasons our climate data was unable to point towards consistent patterns of effect, so speculation here is unwarranted, however further research both using more detailed (e.g., more geographically local, rather than our average of around 10km distance from weather station to house), and more generalised (e.g., annual averages for a region, as per Norback et al.,) may be worth future attention.

6.3.4 Strengths and limitations

The methodological approach and specific methods used to assess indoor dampness and mould in this study have considerable strengths, but also, as noted throughout, some weaknesses. These are discussed below.

6.3.4.1 Strengths

- A comprehensive assessment of house characteristics along with measures of indoor dampness was conducted in the same survey. This allowed for a detailed investigation of the determinants of indoor dampness, providing an evidence-base to inform the design of interventions to reduce these exposures.

- Three almost identical iterations of the survey were conducted, allowing comparisons between them. Since the sample sizes of all three surveys were relatively small, this allowed for an additional robustness check, by assessing their consistency across the three survey iterations.

- The two later surveys used random sampling techniques and included rental houses, allowing us to make generalisations to the broader New Zealand housing stock.

- Variables defining the condition of specific building envelope features (roof, wall claddings, windows, spouting and guttering, and exterior paint) allowed us to examine house condition in greater depth compared to previous large housing surveys exploring dampness and mould, which generally only used an overall assessment of repair or maintenance for the house.

- Inspector-assessed visible mould, subjective dampness and musty odour, meant the measures were more standardised, and undertaken by fewer individuals, reducing the variability (due to individual bias) of the assessment in comparison to self-reported dampness outcomes.

- Moisture measurements allowed us to compare subjective dampness assessments with objective measurements, allowing us to make comparisons between indoor subjective dampness indicators and moisture held in the buildings framing.

6.3.4.2 Limitations

- There is no gold standard definition of indoor dampness, so it is impossible to gauge what proportion of our sample had dampness issues severe enough to be considered harmful to health.
- There was no information available on the health of occupants, meaning we cannot draw conclusions about health impact of occupants or a health-based threshold. Neither can we say which dampness measures are related most closely to adverse health effects.

- Information on the heating and ventilation behaviours of occupants was not collected. Such information could be expected to influence indoor dampness and mould, so it is an important gap.

- The samples were relatively small, although this problem was somewhat mitigated by making comparisons across the three iterations of the survey.

- Our data were cross-sectional, and measures of dampness taken at a single point in time may not be representative of longer-term dampness problems.

- Although conjoined houses and town houses were included, particularly in the later two surveys, apartments were poorly represented.

- Although clustered sampling was used in later surveys, we do not have information on response rates within these clusters.

6.3.4.3 Discussion of strengths and weaknesses

An important strength of this study is that we were able here to make a deep and nuanced analysis of construction and condition characteristics of the most common house typologies, to assess patterns in the relationship between house characteristics and indoor dampness and framing moisture.

The cross-sectional design of the study means that there was no repeated sampling. Such a design would be useful to link outcomes to causes, since they mean that you can test whether an increase in the severity of a hypothesised “cause” (e.g., BEC) is associated with a similar increase in the measured “effect” (e.g., dampness), which was not possible here. The lack of response rate information, despite clustered sampling in the two latter surveys, mean that the samples can only be seen as partially representative of the building stock in New Zealand, as a whole. While the two later surveys improved the geographical representativeness, by using clustered sampling, it is likely that socio-economic differences remain, compared to the actual population. Personal communications with the BRANZ House Condition Survey team, revealed that houses in the very worst condition, and households in the lowest socio-economic strata are less likely to participate in such intrusive research. The extent of potential bias and how this has affected the results is not known.

Importantly apartments were poorly represented, and to a lesser degree, conjoined houses (e.g., townhouses) were also underrepresented, compared to the national building stock, so characteristics associated specifically with these typologies are not covered here.

We were able to include some information about householders' characteristics, including tenure status and number of occupants, however, there was no information available on occupant behaviour, or health of occupants. Furthermore, the original research agreement with participants precluded contacting them for follow-up information, or matching houses to health information available in the Stats NZ integrated data infrastructure (IDI). This limited the ability to understand the health implications of the associations identified in this research. Also, as discussed before, it prevented further analyses on how occupant behaviour affected the observed associations.

6.4 Recommendations and future research

Validation of indoor dampness assessments is of critical value. Work to improve consistency in such assessments is urgently needed. This thesis showed that while objective assessments are valuable, and can be used to improve understanding of the more subjective assessments, moving away entirely from subjective assessments is not justified. Measurement of subjective indicators, moisture levels in materials alongside measurements of moisture in framing, interior surfaces (e.g., wall surfaces) and moisture in air (e.g., RH) may bring further clarity to understanding how best to design interventions for reducing these exposures.

While our study was not able to fully discount the impact of inspector bias from these measurements, due to the same inspector undertaking both the objective and subjective measurements, future studies could mitigate this issue by having a different inspector taking each (objective/subjective), or by ensuring moisture measurements were conducted after assessments of subjective indicators.

Dampness, mould and musty odour can be expected to fluctuate over time, even in the same house. While inspector-assessed measurements potentially reduce bias, these lack perspective of how typical the conditions, on the day of the inspection, may be for that particular house. Adding a short, standardised survey for householders on the frequency of their noticing and (separately) cleaning visible mould is recommended.

Results of our study may be easily replicable in house condition surveys from other countries. Larger samples from such surveys in countries such as the UK, and United

States of America, can be expected to produce more accurate effect estimates for the associations identified here, and such replication of our methods may prove useful, as well as more relevant to countries with houses built using different construction styles and methods

A house condition survey, if it includes measures of indoor dampness, can be effectively used to identify, and perhaps even prioritise in terms of risk, causes of indoor dampness and mould. While this method is useful for identifying these associations, causality would need to be proven using a different methodology. House interventions can be used for assessing the causality of these relationships, but preferably they should focus on one intervention at a time. Numerous studies evaluating social interventions to improve housing, have assessed a "package" of improvements, particularly for energy efficiency, but this "package" effect has limited the capacity to draw specific conclusions. It is the author's recommendation that where feasible, interventions should be designed to facilitate the evaluation of specific components independently, and this would be invaluable for contributing to a broader understanding of this topic.

The condition of the building envelope is relatively straightforward to assess, particularly in low rise-buildings, while in high-rise buildings, drone footage may suffice. This particular assessment could improve exposure assessment in epidemiological studies that aim to measure associations between indoor dampness and harmful health effects. The strength of the effects between indoor dampness and the BEC domain as defined in the work described in this thesis suggest that assessing associations between the BEC domain and harmful health effects may provide important new insights. Such studies are strongly recommended and could contribute to the design of effective interventions to protect health. A clear link between the BEC domain identified here, and health harm would be strong evidence in support of establishing house maintenance standards.

Climate change is likely to increase the prevalence of dampness and mould in Aotearoa New Zealand (as throughout the world), with average temperature and humidity increasing [17]. Furthermore, expected increases in wind-driven rain mean that good building envelope condition is likely to become even important to protect occupants from indoor dampness and mould and its associated adverse health effects [17]. Work to quantify climate change-associated indoor dampness and mould throughout Aotearoa is urgently needed.

During completion of this thesis, the author consulted with the New Zealand Ministry for Business Innovation and Employment, during their development of the “Healthy Homes Standards” (HHS). Several of the characteristics that were associated with increased dampness and mould in this thesis are included in the HHS, which are legal standards for rental houses, and came into effect for private landlords in any new tenancy started from 2021, and will do in existing rental tenancies by 2025. Publicly owned rental houses need to be compliant by 2024. Those characteristics include the requirement for a ground vapour barrier for rental houses with an enclosed subfloor space, effective kitchen and bathroom extract ventilation (or an acceptable continuous ventilation solution), and minimum levels of ceiling and underfloor insulation. Since the 2015 House Condition Survey (HCS), an adapted version of this survey, the “Pilot Housing Survey” (PHS) has been developed by BRANZ, including survey items designed specifically to assess these Healthy Homes Standards. This survey was run in 2018, prior to the standards coming into effect, and are linked to the Stats NZ integrated data infrastructure (IDI), meaning that the (deidentified) participating householders can be linked with their health records. This analysis could allow for an assessment of the success of the HHS in terms of whether people are in fact healthier as a result of these standards and would be particularly valuable if a repeat of the PHS is conducted when all the standards are fully in effect.

While the full House Condition Survey is large and complex, the use of a simplified version, focusing only on the external house characteristics and condition is simple enough to be conducted by a trained assessor. This has been piloted with success (see below for discussion) and would be a valuable addition to assessments of houses of children with particularly problematic asthma and other difficult chronic health conditions, that are conducted by medical officers of health, and by Regional Public Health organisations. Collecting such data may also contribute to a better understanding of the broader implication of living in poorly maintained housing. Such an inclusion may also add visibility into those extreme ends of the socio-economic curve, that may not be well represented in House Condition Surveys, as discussed previously.

While the information here on condition of the building envelope has usefully identified specific attributes which are associated with dampness outcomes, more work is needed to understand if poorly maintained building envelopes are also associated with poorer health outcomes, which may lead to the inclusion of building envelope condition as one of the aspects focused on in the healthy housing standards. Without such evidence (linking poor condition building envelopes and health) there may remain a lack of urgency that would be required to drive government policy toward change. Research to establish a clearer link between house characteristics and condition with adverse health outcomes is needed.

The author is currently involved in an evaluation of an intervention involving the installation of heat pumps in the homes of low-income families. These recommendations have been incorporated into the design of the study, which included a survey with householders and a building inspection. An external inspection based on the domains within the BEC variable was included, and fieldworkers were trained in its use using a large database of photographs to define the condition of each component, along with a supervised inspection. While analysis of the data from this study is ongoing, initial results showed that the BEC variable in this study was associated with the effectiveness of the intervention [15]. Questions were included on heating and ventilation behaviour, as well as typical conditions of the house in terms of dampness, mould, musty odour and airtightness. These questions have been structured to capture broad trends with a moderate degree of detail as follows:

- Which type of heater is typically used in each room? *None; Electric portable; Electric fixed; Gas portable; Gas fixed; Heat pump; Enclosed fireplace; Open fireplace*
- (For each heater and room indicated above) At what time of day do you use the _X_ heater in _X_ room?: *Morning; Afternoon; Evening; Overnight.*
- Do you use the Bathroom extract/open bathroom window during or immediately after showering or bathing? *Every time; Most times; Sometimes; Never.*
- Do you use the Kitchen extract/open kitchen window during or immediately after cooking? *Every time; Most times; Sometimes; Never.*
- Do you air out your bedroom by opening windows wide for at least ten minutes? *Every day; Most days; Some days; Never.*
- How often do you notice visible mould in living and bedrooms? *Never; Sometimes; Often; Always.*

- How often do you notice dampness in living and bedrooms? *Never; Sometimes; Often; Always.*
- How often do you notice a musty or mouldy odour in living and bedrooms? *Never; Sometimes; Often; Always.*
- Do you consider your house draughty? *Never; Sometimes; Often; Always.*

It is recommended that future house condition surveys should also include questions similar to the above in future iterations. It should be noted that most of these questions (except for the time-of-day heating question) are drawn from the General Social Survey (GSS), and therefore, they are included in the 2018 PHS, the sample of which was drawn from GSS participants.

Future iterations of the HCS or PHS should also consider including a subsample of houses from the previous survey, to conduct repeated measures, as is now included in the English House Condition Survey. Such a design provides a greater ability to draw conclusions on the causal relationships between characteristics, including condition, and indoor environmental outcomes.

6.5 General conclusions

Based on the combined results of analyses of data from the 2005, 2010 and 2015 New Zealand Housing Condition Surveys reported in this thesis (Chapters 3-5), the following conclusions were drawn:

- More extract ventilation in wet areas (kitchen, bathroom and clothes dryer) is associated with reduced indoor subjective dampness, visible mould and musty odour in a dose-dependent manner. Presence of extract ventilation is not associated with moisture measurements in ceiling and floor joists. (Aim 1, see chapter 1)

- More insulation (in ceiling, underfloor and wall cavity) is associated with a reduced likelihood of indoor dampness, with evidence of dose-response patterns for visible mould, subjective dampness, and musty odour. Insulation was not associated with moisture measurements in floor and ceiling joists. (Aims 1 & 4)
- Houses rated as poorly maintained (in a single overall rating) are associated with an increased likelihood of subjective indoor dampness, musty odour, and visible mould, with strong evidence of dose-response patterns. Poor house maintenance was not associated with moisture measured in ceiling and floor joists. (Aims 2 & 4)

- Poorer condition of the building envelope (BEC) is associated with increased likelihood of subjective indoor dampness, musty odour, visible mould indoors and floor joist moisture, with strong evidence of dose-response patterns (Aims 3 & 4).

- Visible mould is positively associated with subjective indoor dampness and musty odour, with strong evidence of a dose-response pattern (Aim 5).

- Houses with subjective indoor dampness and musty odour were both associated with higher measured moisture in floors and ceilings. Visible mould was not associated with measured moisture (Aim 5).

- Climate zone is an independent predictor of visible mould, with those houses in the northern climate zone consistently associated with higher, and houses in the southern zone consistently associated with lower likelihood of having indoor visible mould compared to houses in the intermediate zone. There was also some, but weaker, evidence of lower floor joist moisture in the southern climate zone (Aim 6).

- Climate zone was not associated with indoor subjective dampness, musty odour and ceiling joist moisture (Aim 6).

- 30-day rainfall and daily high temperature were not clearly associated with indoor dampness, mould and moisture measurements (Aim 6).

Taken together, the evidence presented in this thesis suggests that maintenance of the external waterproofing elements of dwellings (the building envelope) is associated with indoor dampness and mould, and future epidemiological surveys, including those undertaking assessment of health effects, should include this information in the data collection. More work is needed to continue working towards standardised assessment protocols and the identification of harmful exposure threshold levels of dampness suitable for creating acceptable health-based indoor dampness standards.

6.6 References

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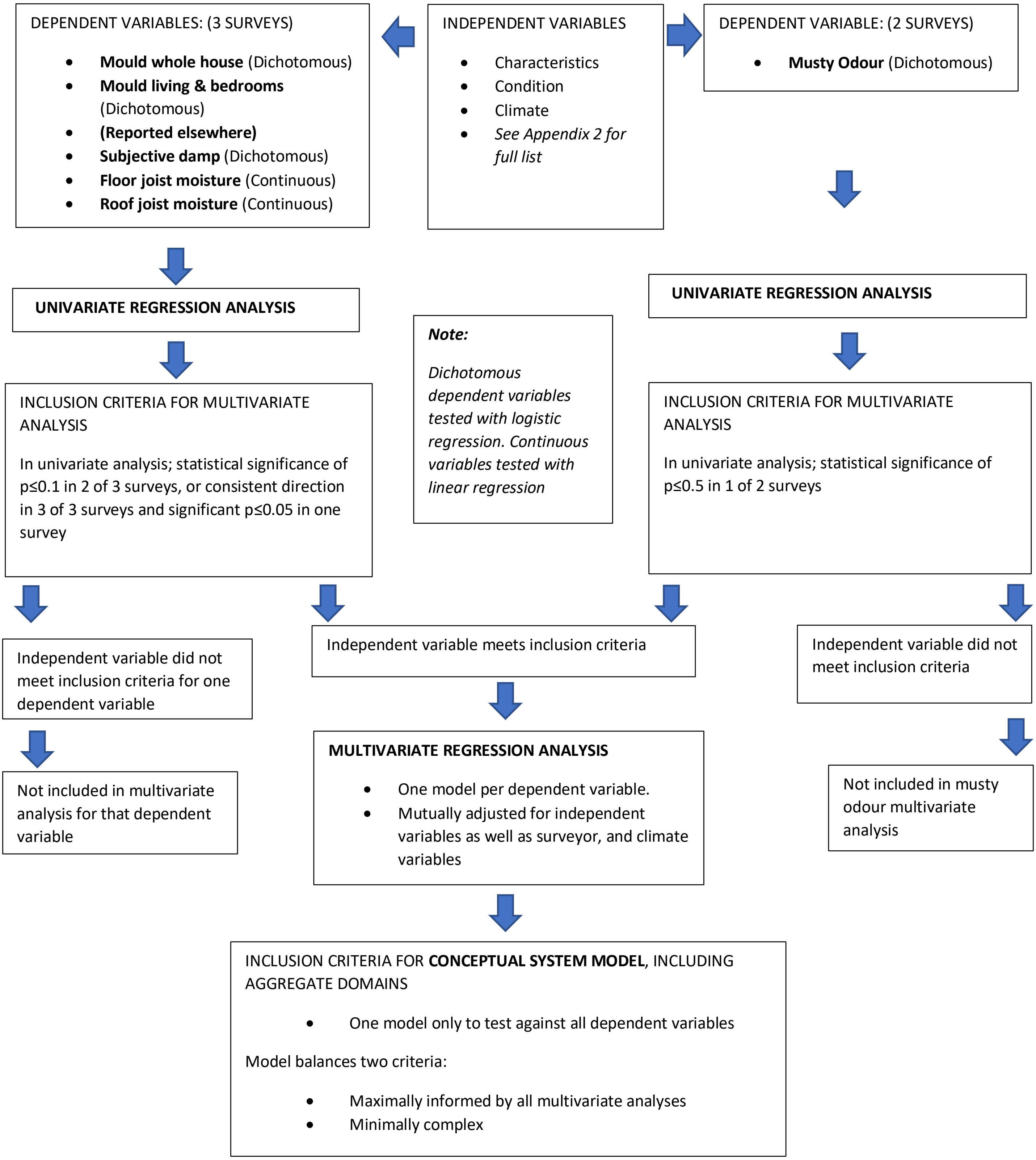
7 APPENDIX 1.

HOUSE CONDITION SURVEYS ANAYSIS FLOW DIAGRAM



DEPENDENT VARIABLES: (3 SURVEYS)

- **Mould whole house** (Dichotomous)
- **Mould living & bedrooms** (Dichotomous)
- **(Reported elsewhere)**
- **Subjective damp** (Dichotomous)
- **Floor joist moisture** (Continuous)
- **Roof joist moisture** (Continuous)

INDEPENDENT VARIABLES

- Characteristics
- Condition
- Climate
- *See Appendix 2 for full list*

DEPENDENT VARIABLE: (2 SURVEYS)

- **Musty Odour** (Dichotomous)

UNIVARIATE REGRESSION ANALYSIS

INCLUSION CRITERIA FOR MULTIVARIATE ANALYSIS

In univariate analysis; statistical significance of p≤0.1 in 2 of 3 surveys, or consistent direction in 3 of 3 surveys and significant p≤0.05 in one survey

Note:

Dichotomous dependent variables tested with logistic regression. Continuous variables tested with linear regression

UNIVARIATE REGRESSION ANALYSIS

INCLUSION CRITERIA FOR MULTIVARIATE ANALYSIS

In univariate analysis; statistical significance of p≤0.5 in 1 of 2 surveys

Independent variable did not meet inclusion criteria for one dependent variable

Not included in multivariate analysis for that dependent variable

Independent variable meets inclusion criteria

MULTIVARIATE REGRESSION ANALYSIS

- One model per dependent variable.
- Mutually adjusted for independent variables as well as surveyor, and climate variables

Independent variable did not meet inclusion criteria

Not included in musty odour multivariate analysis

INCLUSION CRITERIA FOR **CONCEPTUAL SYSTEM MODEL**, INCLUDING AGGREGATE DOMAINS

- One model only to test against all dependent variables

Model balances two criteria:

- Maximally informed by all multivariate analyses
- Minimally complex

8 APPENDIX 2

Variables tested	**2005**	**2010**	**2015**	**Categorisation for univariate and multivariate analyses**	**Aggregation for domains**
Total rainfall over previous 30 days	✓	✓	✓	Continuous	continuous
Average daily high temperature over previous 30 days	✓	✓	✓	Continuous	Continuous
Range hood (extract over cooker)	✓	✓	✓	Included in count of kitchen extract ventilation (max of one) Yes No	**Ventilation domain** (1 of 3) No =0 Yes =1
Other mechanical kitchen ventilation	✓	✓	-		
Indoor clothes dryer ventilation ducting present	✓	✓	✓	No dryer present Dryer not ventilated Ventilated to outside Ventilated to roof space	**Ventilation domain** (1 of 3) If dryer present and ducted to the outside =1 All other options =0
Bathroom extract ventilation fan	✓	✓	✓	No Yes	**Ventilation domain** (1 of 3) No =0 Yes =1
Ceiling space insulation % coverage 0-25% 30-75% Over 75%	✓	✓	✓	Combined insulation index Least Mid Most	**Insulation domain** (1 of 3 reverse coded) Most =0 Mid/Least =1
Ceiling space insulation thickness Less than 50mm 50-100mm Over 100mm	✓	✓	✓		
Wall Insulation	✓	✓	✓	No Yes	**Insulation domain** (1 of 3 reverse coded) No =1 Yes =0
Underfloor insulation (>50% coverage)	✓	✓	✓	Yes No	**Insulation domain** (1 of 3 reverse coded) No =1 Yes =0
Ground cover under house (>50% coverage)	✓	✓	✓	No Yes	**Subfloor defect domain** (1 of 3) If house has a suspended floor Yes =0 No =1
Plumbing leaking under house	✓	✓	✓	(Combined with Ponding under house; max =1) No =0 Yes =1	**Subfloor domain** (1 of 3) If house has a suspended floor Plumbing leaks or ponding under house =1 All other options =0
Water ponding under house	✓	✓	✓	(Combined with Plumbing leaks under house; max =1) No =0 Yes =1	
Subfloor ventilation above/below requirements	✓	✓	✓	Yes No	**Subfloor domain** (1 of 3) If house has a suspended floor No =1 All other options =0
Wall cladding condition	✓	✓	✓	Excellent/Good=0 Moderate/poor/serious =1	**BEC domain** (1 of 5) No =0 Yes =1
Spouting and guttering condition rating	✓	✓	✓	Excellent/Good=0 Moderate/poor/serious =1	**BEC domain** (1 of 5) Excellent/Good=0 Moderate/poor/serious =1
Wall cladding paint deterioration	✓	✓	✓	No Yes	**BEC domain** (1 of 5) No =0 Yes =1
Windows condition rating	✓	✓	✓	Excellent/Good=0 Moderate/poor/serious =1	**BEC domain** (1 of 5) Excellent/Good=0 Moderate/poor/serious =1

Roof condition rating	✓	✓	✓	Excellent/Good=0 Moderate/poor/serious =1	**BEC domain** (1 of 5) Excellent/Good=0 Moderate/poor/serious =1
Climate zone	✓	✓	✓	North Mid South	North Mid South
Owner occupied/rental	-	✓	✓	Owner Tenant	Owner Tenant
Number of occupants	✓	✓	✓	1-2 3-4 5 or more	1-2 3-4 5 or more
General maintenance assessment	✓	✓	✓	Excellent/Good=0 Moderate =2 Poor/serious =3	Excellent/Good=0 Moderate =2 Poor/serious =3
Surveyor	✓	✓	✓	ID no.	ID no.
Age of house	✓	✓	✓	Pre 1930 1930-1979 Post 1980 Missing/mixed	-
Date of assessment (aggregated by month and season)	✓	✓	✓	Dec-Feb (Paper 1 Dec-Mar) Mar-May June-Aug Sep-Nov	-
No. of storeys	✓	✓	✓	-	-
No. bedrooms	✓	✓	✓	-	-
Floor area	✓	✓	-	-	-
Close to busy road (combined with Noise)	✓	✓	✓	(max of 1) Not close to busy road =0 Close to busy road =1 Always/mostly quiet =0 Moderate/loud noise =1	-
Noise	✓	✓	✓		
House in shade	✓	✓	✓	No/some shade Shady most/all day	-
House sheltered/exposed	-	✓	✓	-	-
House built on slope	✓	✓	✓	-	-
Type and number of heaters	✓	✓	✓	Number of gas appliances (heaters, fixed portable and oven/stove) Number of electric appliances (heaters, fixed portable and oven/stove) Number of enclosed fire places/pellet burners Number of open fire places	-
Heating behaviour	-	-	✓	-	-
Air conditioner	✓	✓	✓	Included in count of electric heaters (=1)	-
Dehumidifier	✓	✓	✓	-	-
Heat recovery air treatment	✓	✓	✓	-	-
Cooker electric/gas	✓	✓	✓	Included in count of gas/electric heaters	-
Floor coverings living room/bedrooms	✓	✓	✓	-	-
Signs of leaking indoors	✓	✓	✓	Combined with roof leaks and signs of leaking internal gutters No Yes	-
Foundation type (concrete slab, piles, perimeter wall)	✓	✓	✓	-	-
Basement present	✓	✓	✓	-	-
Basement signs of leaks	✓	✓	✓	-	-
Cladding deterioration near ground	-	✓	✓	-	-
Subfloor vents covered by vegetation	✓	✓	✓	-	-
Subfloor ventilation condition rating	✓	✓	✓	Excellent/Good=0 Moderate/poor/serious =1	-
Wall cladding minor cracks	✓	✓	✓	-	-
Wall cladding holes/major cracks	✓	✓	✓	-	-
Ext. doors condition rating	✓	✓	✓	-	-

Roof material	✓	✓	✓	Metal Concrete/clay tile Missing/mixed/other	-
Roof slope	-	✓	✓	-	-
Roof leaks	✓	✓	✓	Combined with Signs of leaking indoors (max=1) No Yes	-
No. of spouting defects	✓	✓	✓	-	-
Internal gutters leaking	✓	✓	✓	Combined with Signs of leaking indoors (max=1) No Yes	-
Window material	✓	✓	✓	Timber Metal Missing/mixed/other	-
Windows double glazed	✓	✓	✓	50% or less =0 >50% =1	-
Window flashing deterioration	✓	✓	✓	Combined with window flashings missing (max=1) No Yes	-
Window flashings missing	✓	✓	✓	Combined with window flashing deterioration (max=1) No Yes	-
Windows joint cracks	✓	✓	✓	-	-
Windows missing/cracked putty	✓	✓	✓	-	-
Windows missing/shrunk rubber seals	✓	✓	✓	-	-
Windows leaking	✓	✓	✓	-	-
Windows paint deterioration	✓	✓	✓	-	-
Internal gutters leaking	✓	✓	✓	Combined with Signs of leaking indoors (max=1) No Yes	-
Spouting and guttering holes	✓	✓	✓	Number of spouting/guttering defects 0-5	-
Guttering – reverse flow	✓	✓	✓		
Spouting and guttering joint leaks	✓	✓	✓		
Spouting and guttering corrosion	✓	✓	✓		
Missing guttering/downpipes	✓	✓	✓		