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Risk factors for moisture damage presence and severity in Finnish homes

RESEARCH

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ABSTRACT

Moisture-damaged buildings are a prominent issue in Finland, but with limited information on damage prevalence, degree of severity and risk factors. This paper analyses 14,996 Finnish detached and semidetached houses that have undergone a standardised moisture assessment of interior spaces and at-risk structures inside the building envelope. Confirmed damage (a binary indicator of damage presence) and a damage index (an ordinal indicator of severity) were calculated for each home and their association with different building and area characteristics estimated. Frequently damaged structures include pre-1950s log walls, walls contacting soil, wooden ground floors and false plinths. Around 15% of surveyed houses had risk structure damage, 19% had at least one confirmed damage anywhere in the house and 49% had either confirmed, likely or possible damage. The greatest risk factor for confirmed damage was house age (odds ratio = 1.48 (95% confidence interval (CI) = 1.45–1.51) for each decade since construction), with nearly half of all houses built pre-1939 damaged. Other risk factors explained a third of the effect of building age, and included log external walls, fibreboard roofs, absence of mechanical ventilation, detached properties and wind-driven rain precipitation. Results can support targeted remediation efforts, protect health and estimate exposure–response relationships for moisture damage.

PRACTICE RELEVANCE

Moisture damage in homes causes various health concerns for occupants, and in colder climates such as Finland such damage often occurs within the building structure. This study finds confirmed moisture damage in 19% of surveyed Finnish homes. Most damage was within the building structure, supporting the need for surveys investigating inside known-risk structures. Older homes had much higher damage risk, reflecting different construction methods and ageing, but also suggesting modern building standards are helping to reduce damage. Increased risk in higher wind-driven precipitation regions

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indicates a need for regulations and research that improve the resilience of all housing to the projected increases in driving rain from climate change. Understanding the building characteristics and structures that increase moisture risk can support targeted remediation and maintenance in vulnerable buildings, conserve older buildings and avoid demolition, and help protect occupant health.

1. INTRODUCTION

Indoor moisture and mould are issues with significant health, wellbeing and economic implications. They have been associated with a range of health problems in occupants, with the best evidence for asthma and respiratory infections (Mendell *et al.* 2011). In children, visible mould and mould odour are associated with asthma development and exacerbation (Caillaud *et al.* 2018), and it is estimated that around 15% of new childhood asthma cases in Europe can be attributed to dampness, representing over 69,000 potentially avoidable disability-adjusted life years (DALYs) and 103 potentially avoidable deaths every year (WHO 2011). Damp housing may also lead to various mental health stressors, *e.g.* occupant concerns over the health impact of poor living conditions (Liddell & Guiney 2015). Evidence for health risks is strongest in studies with observed factors, such as inspections that indicate the presence of moisture damage or mould. A key research challenge in indoor moisture and health, however, is the lack of evidence on the exposure–response association, or how the amount of exposure to moisture damage relates to health outcomes (Mendell & Adams 2019). Moisture assessments that characterise the extent of damage are an important way to understand these associations.

The prevalence of moisture damage in the Finnish building stock is low relative to elsewhere in Europe (Gunnbjornsdottir *et al.* 2006; Haverinen-Shaughnessy 2012; Haverinen-Shaughnessy *et al.* 2012; Norbäck *et al.* 2017; WHO 2011). However, symptoms related to poor indoor air quality (IAQ) are commonplace (Koponen *et al.* 2018) resulting in an estimated €450 million annually for treating symptoms and loss of work productivity (Reijula *et al.* 2012) and €400 million repairing moisture damage (Nippala & Vainio 2016). Due to this significant health and economic burden, there has been considerable research, public, media, and political interest on damp and IAQ issues in Finland (Lampi *et al.* 2020), and various studies have examined the prevalence of damp in the Finnish building stock. A report to the Finnish parliamentary audit committee estimated that around 6–10% of houses, 12–18% of schools and kindergartens, 20–26% of care institutions, and 2.5–5% of office buildings had damp or mould (Reijula *et al.* 2012). Other studies have detected signs of damp or mould in 24% of surveyed school buildings (Haverinen-Shaughnessy *et al.* 2012) and 44% of surveyed office buildings (Salonen *et al.* 2007), while over 80% of surveyed dwellings have shown signs of current or past moisture damage (Nevalainen *et al.* 1998). Another Finnish study found damp in 52% of houses, and mould in 27%, with exposure to moisture significantly associated with self-reported respiratory symptoms (Koskinen *et al.* 1999).

In colder climates such as Finland, visible mould is relatively rare (Annila *et al.* 2016; Haverinen-Shaughnessy *et al.* 2012; Karvonen *et al.* 2009; Salonen *et al.* 2007) and most problems are hidden within building structures (Annila *et al.* 2016). This is due to both climate and construction. Low wintertime outdoor water vapour levels mean that the dominant humidity load to the building envelope comes from interstitial condensation of indoor air diffusing outdoors, precipitation and leaking pipes. Other common causes of moisture problems include moisture from the ground and built-in moisture. Construction characteristics include differences in ventilation capability to remove damp indoor air, and building envelope design and condition which impacts interstitial and surface temperature, moisture levels and building material sensitivity to damage. While the percentage of buildings with visible mould is low, mould spores, their structural and metabolic components can move from within structures to the indoor air via airflow through cracks and joints (Airaksinen *et al.* 2004; Komulainen *et al.* 2003; Suonketo & Pessi 2000). Without visible signs of moisture damage, inspections are typically not undertaken until occupants exhibit symptoms of exposure, and repairs may not be performed until two to five years from the initial onset of symptoms (Peltola & Asikainen 2009).

There are envelope structures known to be problematic in Finnish buildings, and inspection guidelines have been developed to investigate moisture damage within these so-called risk structures (Annila *et al.* 2016; Pitkäranta & Weijo 2022), elsewhere within and outside the building, as well as assessing air leaks, ventilation systems and indoor air conditions. Results of these surveys provide opportunities to understand the types of moisture damage in Finnish houses, build upon the relatively few studies that have examined the amount of damage (or dose) in damaged buildings (Chelelgo *et al.* 2001; Haverinen *et al.* 2003), and better understand how to manage and prevent moisture damage. Therefore, this paper aims to understand the prevalence, degree of and risk factors for moisture damage in Finnish housing. This will be achieved by analysing a database of around 15,000 detached and semidetached homes surveyed as part of a pre-sales moisture condition survey. The objectives are as follows:

- To analyse the prevalence of different risk structures, the rates of damage within these structures, as well as other moisture damage on building surfaces
- To understand the major determinants of moisture damage in the homes and calculate the odds ratio of moisture damage for houses of different construction and environmental characteristics using logistic regression
- To develop a moisture damage index that can be used to describe the severity of damage in houses, and to perform an ordinal logistic regression against construction and environmental characteristics.

2. METHODS

2.1 SURVEY DATA

Anonymised housing data were provided by Raksystems Insinööritoimisto Oy (Raksystems) for 14,996 homes surveyed across Finland between 2016 and 2020 as part of the pre-sales housing condition assessment. The database includes surveys performed in detached, semidetached and ‘other’ buildings such as cottages and auxiliary buildings, but does not include dwellings such as terraced houses and apartment buildings that are part of housing cooperatives. Due to low numbers, all buildings marked as ‘other’ were removed, resulting in 14,873 buildings.

Surveyed buildings were inspected in accordance with technical guide KH-90-00394 (Rakennustieto Oy 2007), a Finnish standard that defines the content and scope of housing inspections, the measurements to be made and the reporting responsibilities of the inspector. Before the physical inspection, interviews with the occupant and/or the owner were conducted and the documentation related to the building reviewed. If the building has a property manager, they are also interviewed, and prior condition assessments made on the property are examined.

The subsequent physical survey is mostly an organoleptic, superficial and non-destructive inspection. The survey systematically inspects risk structures, or specific building envelope structures listed in technical guide KH-90-00394 that have been found to be susceptible to moisture damage (Table 1). Such structures usually complied with building regulations at the time of construction before their poor moisture performance was recognised. Inspections are made through structural openings or, if necessary, a maximum of three holes can be drilled into the building envelope to look for damage. If present in the home, the investigated risk structures within the houses are then classified as follows:

- *No damage*: the risk structure has been inspected through structural openings or holes, with no indication of damage
- *Unopened and further investigation required*: the risk structure has not been opened and inspected. This may be because it is technically difficult, or because the seller has not granted permission
- *Opened and further investigation required*: the risk structure has been inspected through structural openings, but further investigation is required to confirm suspected damage

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- *Verified damage*: the risk structure was observed to have clear moisture damage either with or without making a structural opening.

The inspection also includes an examination for moisture damage surfaces inside and outside the building, abnormal odours, and inspections of the drainage and ventilation systems. Mould and moisture damage that is not inside risk structures (referred to here as 'Other' damage) are classified as binary presence/absence of issues in the inspected locations.

2.2 DATA ANALYSIS

The present analysis includes only observations in risk and other structures that can affect the IAQ of the home (*i.e.* damage directly located or with clear air connections to living areas) (Table 1). Moisture damage in wet rooms is excluded, as the survey defaults to recommending renovation for these rooms when they are past their technical lifespan irrespective of whether or not damage is present.

Table 1: Inspected risk structures and other locations included in the analysis

Note: For more details on the risk structures, see Raksystems (2023).

	INSPECTED ELEMENT	POSSIBLE DAMAGE
Risk to structure	Attic ventilation	Insufficient ventilation in the attic space under a pitched roof leads to moisture damage
	Double concrete slab (sandwich) structure	Thermal insulation is sandwiched between a foundation slab below and a second concrete casting above. Soil moisture, or leaks from pipes, may move into the insulation layer particularly if there are partitions
	False plinths	Walls of buildings are supported by a plinth directly or with a wooden undercut below the ground, which can result in a floor level lower than the ground level. Damage can occur from soil moisture and condensation of indoor air
	Flat roof	Defects in flat roofing can lead to water penetration and may have problems with attic space ventilation
	Low foundation height	Occurs when the ground floor is too close to the ground level (less than 100 mm in existing buildings or 300 mm in new buildings)
	Outer wall ventilation	Lack of ventilation in external timber walls means that moisture may accumulate in wall cavities. Water vapour can enter the wall cavity due to missing or inadequate vapour barriers, while ventilation can be impacted by lack of vents or latex paints
	Partition wall below floor level	If the partition is in contact with soil, this can lead to damage from soil moisture
	Pre-1950s log wall	In older log homes, the wetting of logs and condensation can lead to decay over time
	Skylight or roof window	Cracks or poor installation of skylights can lead to moisture ingress, while condensation can occur on the inner surface
	Walls in contact with soil	Walls in contact with soil and with internal insulation suffer from moisture ingress and condensation
	Wooden ground floor over a concrete slab	In older homes, ground floors may be constructed on wooden floorboards on top of a concrete slab. This can have problems with moisture ingress from the soil and condensation from indoor air
Other damage	Abnormal indoor odour	A smell of microbial growth/mould is detected in the house
	Attic damage	Confirmed moisture damage in the attic floor
	Attic floor air leakage	Evidence of air leakage through the attic floor which is likely to have caused damage
	Attic membrane damage	A vapour-permeable membrane, plastic sheeting or flooring is on top of thermal insulation in the attic and confirmed damage has been found
	Cold storage	A cold storage pantry inside the home can have possible damage
	Concrete subfloor damage (unconfirmed)	Likely damage on the concrete subfloor

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INSPECTED ELEMENT	POSSIBLE DAMAGE
Crawl space damage	Moisture damage is confirmed in the crawl space
Crawl space microbial growth (unconfirmed)	Evidence of likely microbial growth is found in the crawlspace
Crawl space damage (unconfirmed)	Evidence of likely moisture damage is found in the crawl space
Kitchen sink damage	Evidence of water damage from leaks in the kitchen
Post-1950s log frame damage	Confirmed damage to a modern log frame external wall. This damage is not captured in the risk structure examination, which focuses specifically on log walls in homes built pre-1950
Other interior damage	Generic description of confirmed moisture damage not included in the other categories, *e.g.* a sink drain that leaks and causes damage to a floor and/or wall structure
Other interior damage (unconfirmed)	Generic description of possible but unconfirmed moisture damage in building components not included in the other categories. These may include, *e.g.* marks made by water that are now dry and without a visible cause
Other interior surface damage (unconfirmed)	Generic description of likely but unconfirmed moisture damage not included in the other categories on surfaces. These may include, *e.g.* marks made by water that are now dry and without a visible cause
Wood cladding damage (unconfirmed)	Further investigation is required to confirm possible moisture damage in wood cladding
Wooden ground floor damage	Confirmed damage is visible on a wooden ground floor

Analysis of the dataset was performed in R version 4.2.1. To account for resident sociodemographic differences, the local median household income (2020) from Statistics Finland (Tilastokeskus 2023) was divided into quantiles and joined to the dataset based on the dwelling postcode. Climatic differences were accounted for by linking dwellings to wind-driven precipitation exposure regions by dwelling municipality. These regions were derived using 30-year average (1989–2018) climate data (Laukkarinen *et al.* 2022) (see Figure S1 in the supplemental data online).

Summary statistics were then calculated, evaluating the representativeness of the dataset by comparing it with housing data from Statistics Finland, and identifying the frequency of different types of risk structure and other damage.

The categorised risk structure observations were then combined with the other observations to create two dependent variables to indicate the presence of moisture damage in the home: a binary indicator of the presence of at least one verified moisture damage that may impact indoor air (confirmed damage) and an ordinal-scale variable describing the combined severity of all moisture damage observations in the house (damage index).

To do this, expert judgement was used to categorise damage into *Confirmed*, *Likely*, *Possible* and *No Damage* equivalents, which represent the certainty that damage is present in different locations and the extent to which damage can impact indoor air (Table 2). Confirmed damage was defined as verified damage either within risk structures or an equivalent in other areas of the house. A damage likelihood (1, 2 or 4) was assigned for each category, providing weights that represent the likelihood and potential impact of damage. These were summed for all observations made within a building to derive the ordinal composite damage index.

The first analysis looked at the association of building characteristics with the presence of at least one confirmed damage in homes using logistic regression. The second analysis looked at the association of building characteristics and the damage index using ordinal logistic regression (*MASS* package in R). In both cases, a univariate model for each variable independently (model 1), a multivariate model that adjusted for the age of the building for each variable (model 2) and a full multivariate model that adjusts for all characteristics (model 3) were estimated. The proportional odds assumption in the ordinal logistic regression was confirmed using the Brant test.

Table 2: Classification of the likelihood for moisture damage

Note: The likelihoods for all the different risk structures and other observations were summed to create the composite damage index for the house.

LIKELIHOOD OF DAMAGE	RISK STRUCTURE CLASSIFICATION	OTHER OBSERVATIONS
0 (No observed damage)	The building element does not exist in the house, or if it does there is no moisture damage in the building element, nor further investigation necessary	
1 (Possible damage)	The building element is present in the house, but has not been opened and more investigation is necessary to determine if moisture damage is present	• Cold storage • Wood cladding damage (unconfirmed)
2 (Likely damage)	The building element is present in the house and it has been opened, but more investigation is necessary to determine if moisture damage is present	• Abnormal odour • Attic floor air leakage • Concrete subfloor damage (unconfirmed) • Crawl space damage (unconfirmed) • Crawl space microbial growth (unconfirmed) • Crawl space damage (unconfirmed) • Kitchen sink damage • Other interior surface damage (unconfirmed) • Other interior damage (unconfirmed)
4 (Confirmed damage)	The building element is present in the house and moisture damage has been confirmed	• Attic damage • Attic membrane damage • Post-1950s log wall damage • Other interior damage • Wooden ground floor damage

3. RESULTS

3.1 HOUSING CHARACTERISTICS

The characteristics of the surveyed houses are shown in Table 3. The dataset included homes in every region of Finland, with the majority of inspected homes in the capital region of Uusimaa (49% of inspections), Pirkanmaa (13%) and south-west Finland (10%). These broadly reflect the population distribution in Finland, where Uusimaa (31%), Pirkanmaa (9%) and the south-west (9%) are the most populous regions (Tilastokeskus 2023). The largest proportion of homes were in wind-driven precipitation region I (43%), where wind-driven precipitation is greatest. Higher income postcodes had a greater proportion of surveyed houses.

The dataset was comprised of 91.7% detached houses and 8.3% semidetached houses, similar to the 93% detached and 7% semidetached in the existing stock and providing confidence that the housing types in the database are reasonably representative. The largest proportion were built between 1980 and 1999 (29%, similar to the 27% in official statistics), followed by those built post-2000 (28% versus 21%), and those built from 1960 to 1979 (20% versus 23%); newer buildings are therefore somewhat overrepresented. Houses were mostly constructed in-place (75%) as opposed to prefabricated/element construction. Other common construction characteristics included concrete slab ground floors, outer walls constructed and cladded with wood, and ridged roofs with tile roofing and an underlay. Mechanical ventilation was present in 58% of homes, while 42% had a gravitational ventilation system.

Table 3: Descriptive statistics for dwellings and construction characteristics, and the frequency of different damage types

CLASS	CATEGORY	COUNT	FRE-QUE-NCY (%)	CONFIRMED DAMAGE IN A RISK STRUCT-URE (%)	CONFIRMED DAMAGE IN A RISK STRUCTURE AND/OR OTHER LOCATIONS (%)	CONFIRMED, LIKELY OR POSSIBLE DAMAGE (%)	ABNORMAL ODOUR (%)	AVERAGE DAMAGE INDEX
All homes	–	14,873	100%	15.2%	19.4%	49.0%	7.3%	2.2
Ages	1720–1939	1,066	7.2%	38.6%	48.3%	84.0%	14.4%	5.3
	1940–59	2,176	14.6%	29.2%	37.1%	74.3%	14.9%	3.9
	1960–79	3,037	20.4%	21.9%	26.7%	72.2%	13.3%	3.3
	1980–99	4,369	29.4%	11.3%	14.8%	44.9%	4.3%	1.6
	2000–20	4,221	28.4%	1.2%	2.7%	14.6%	0.5%	0.4
Floor areas (m^2)	11–50	92	0.7%	21.7%	29.3%	64.1%	13.0%	3.0
	51–74	351	2.6%	24.5%	31.3%	61.5%	10.8%	3.1
	75–100	1,267	9.5%	18.2%	23.6%	55.4%	10.7%	2.7
	101–149	5,827	43.9%	13.9%	18.2%	45.8%	6.1%	2.0
	150–800	5,737	43.2%	13.3%	16.7%	46.6%	6.3%	2.0
Dwelling type	Detached	12,183	91.7%	15.8%	20.1%	48.9%	7.5%	2.3
	Semidetached	1,099	8.3%	10.9%	13.7%	44.9%	4.3%	1.7
Storeys	1	6,292	56.1%	11.8%	15.8%	43.7%	6.9%	1.9
	1.5	1,539	13.7%	12.5%	18.1%	50.2%	5.3%	2.2
	2	3,042	27.1%	11.2%	14.5%	40.9%	4.1%	1.7
	2.5	28	0.2%	7.1%	7.1%	46.4%	0.0%	1.5
	≥ 3	313	2.8%	19.5%	24.0%	55.6%	8.6%	2.7
Cellar	No	11,214	75.4%	11.9%	16.0%	44.2%	6.0%	1.9
	Yes	3,659	24.6%	25.2%	30.1%	63.7%	11.6%	3.2
Construction type	Built in-place	11,054	74.7%	18.7%	23.4%	55.9%	8.9%	2.6
	Element	3,739	25.3%	4.7%	7.7%	27.7%	2.6%	0.9
Ground floor	Stone	13,535	43.2%	15.0%	18.7%	48.4%	7.1%	2.1
	Crawlspace	3,082	9.8%	16.8%	25.1%	51.1%	9.3%	2.7
	Slab-on-ground	12,619	40.2%	15.8%	19.5%	50.1%	7.4%	2.2
	Unknown	198	0.6%	29.3%	36.4%	74.7%	20.2%	4.9
	Wood	1,925	6.1%	22.5%	34.7%	64.5%	12.3%	3.7
External walls	Log	1,247	7.6%	31.0%	39.5%	73.0%	11.6%	4.3
	Stone	2,859	17.4%	12.2%	15.3%	48.4%	7.0%	1.9
	Unknown	43	0.3%	2.3%	7.0%	27.9%	4.7%	1.0
	Wood	12,309	74.8%	15.6%	19.8%	48.8%	7.5%	2.2
Cladding	Wood	10,428	56.3%	15.5%	20.1%	49.1%	7.5%	2.3
	Brick	5,398	29.1%	14.2%	17.9%	53.0%	6.6%	2.1
	Log	356	1.9%	9.8%	16.0%	40.2%	4.8%	1.5
	Render	1,798	9.7%	13.5%	16.6%	44.5%	6.6%	1.9
	Boarding	255	1.4%	31.0%	38.0%	79.6%	20.8%	4.3
	Other	288	1.6%	19.4%	24.0%	54.9%	12.2%	2.8
Roof type	Ridged	12,351	81.8%	15.5%	19.8%	48.3%	7.5%	2.2
	Flat	491	3.3%	19.6%	22.4%	82.1%	10.8%	3.7
	Double-ridged	877	5.8%	17.9%	23.1%	59.0%	6.5%	2.6
	Mansard	241	1.6%	23.7%	29.9%	61.4%	9.1%	3.2
	Split ridge	418	2.8%	6.7%	8.9%	26.8%	4.3%	1.1
	Monopitch	727	4.8%	12.0%	15.5%	46.2%	5.6%	2.0

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CLASS	CATEGORY	COUNT	FRE-QUE-NCY (%)	CONFIRMED DAMAGE IN A RISK STRUCT-URE (%)	CONFIRMED DAMAGE IN A RISK STRUCTURE AND/OR OTHER LOCATIONS (%)	CONFIRMED, LIKELY OR POSSIBLE DAMAGE (%)	ABNORMAL ODOUR (%)	AVERAGE DAMAGE INDEX
Roofing	Sheet metal	4,747	31.6%	7.9%	10.7%	32.5%	2.9%	1.2
	Tile	5,157	34.3%	19.0%	24.2%	55.7%	9.1%	2.7
	Plate metal	3,016	20.1%	19.6%	24.5%	55.6%	10.5%	2.7
	Bitumen	1,724	11.5%	16.4%	21.5%	64.6%	10.3%	2.9
	Fibreboard	397	2.6%	24.4%	28.7%	64.0%	9.8%	3.2
Attic floor	Wood	14,429	91.5%	15.5%	19.8%	49.2%	7.4%	2.2
	Stone	398	2.5%	6.0%	8.8%	41.2%	4.3%	1.2
	Unknown	17	0.1%	11.8%	11.8%	58.8%	5.9%	2.2
	None	705	4.5%	13.6%	17.2%	52.2%	9.2%	2.2
	Flat roof	218	1.4%	21.1%	23.9%	88.1%	12.4%	4.2
Ventilation	Gravity	6,077	41.9%	27.4%	34.0%	73.0%	13.8%	3.8
	Mechanical extraction	2,878	19.8%	13.0%	17.0%	51.6%	6.4%	2.0
	Mechanical input–output	5,525	38.1%	3.3%	5.3%	21.4%	0.9%	0.6
	No system	26	0.2%	26.9%	38.5%	65.4%	19.2%	4.1
Income quantile	1 (lowest)	1,749	11.8%	21.3%	25.6%	59.2%	10.9%	3.0
	2	1,783	12.0%	17.2%	22.5%	51.9%	8.4%	2.4
	3	2,329	15.7%	16.0%	20.4%	51.4%	8.2%	2.4
	4	2,907	19.5%	14.4%	18.7%	48.1%	6.1%	2.1
	5 (highest)	5,988	40.3%	12.9%	16.7%	44.6%	6.2%	1.9
Wind-driven precipitation region	I (highest)	6,522	43.9%	17.0%	21.6%	53.2%	7.8%	2.5
	II	6,225	41.9%	13.7%	17.9%	45.8%	6.0%	2.0
	III	1,962	13.2%	13.8%	17.0%	45.0%	10.1%	2.2
	IV (lowest)	52	0.3%	15.4%	21.2%	59.6%	7.7%	2.3

3.2 MOISTURE RISK

3.2.1 Analysis of risk structure survey

Figure 1 shows the prevalence of different risk structures by construction age, and the percentage that have verified, likely or possible damage. Around 64% of surveyed dwellings had either no damage in risk structures or risk structures were absent. At least one risk structure had verified damage in 15% of houses, at least one 'opened but further investigation required' in 6%, and 22% with at least one 'unopened but further investigation required'.

Across all homes, the greatest number of verified damage in risk structures were in walls in contact with soil (5.5% of surveyed homes), wooden floors above concrete slabs (3.5%) and false plinths (2.6%). However, not all risk structures were present in each building. The risk structures that—if present—were most likely to have verified damage were walls in contact with soil (38.7%), log external walls in homes built pre-1950 (29.6%), wooden ground floors above concrete slabs (22.8%) and low foundation height (20.0%). Flat roofs and roof windows were disproportionately less likely to have been opened and inspected due to accessibility issues, while double slab floors were never opened. Around 4% of dwellings had verified damage in more than one risk structure.

The greatest rates of damage in risk structures were seen in the pre-1939 houses (39% damaged). Many of these older buildings had log external walls, representing the most common risk structure in these houses and the most likely risk structure to be damaged. Houses built between 1940 and 1959 had relatively higher rates of damage due to poor external wall ventilation, poor attic ventilation and walls contacting soil. Buildings built from 1960 to 1979 and from 1980 to 1999 had multiple at-risk structures, including high rates of wooden ground floors, underfloor partitions, walls contacting soil, false plinths, poor external wall ventilation, flat roofs and roof windows. Of these, false plinths were the most common location with confirmed damage. Post-2000 buildings have relatively fewer risk structures, with roof windows being the most common.

Figure 1: Percentage of houses by damage classification in different risk structures and by housing age.

Note: *Due to accessibility reasons, double slab flooring is not opened.

3.2.2 Damage other than in risk structures

The prevalence of other damage types observed by building age is shown in Figure 2. At least one unconfirmed or verified other moisture issue is found in 31% of dwellings, with the highest rates in pre-1939 dwellings (59%) and the lowest in post-2000 dwellings (11%). Around 10% of houses had multiple instances of unconfirmed or verified other damage. The most common type of damage outside of risk structures is a general reference to unconfirmed other surface damage.

Abnormal indoor odour was reported in 7.3% of surveyed houses, highest in buildings without a mechanical ventilation system (18.5% versus 2.8% in mechanically ventilated homes) and more common in older houses (14.6% of those built pre-1939, 14.9% of those built from 1940 to 1959, and 13.3% of those built between 1960 and 1979).

3.2.3 Damage likelihood

Combining observations in risk and other structures enabled these data to be integrated into a combined analysis of individual confirmed, likely and possible damage equivalents. At least one confirmed damage was present in 19% of houses, with 10% of dwellings having multiple instances. Nearly 40% of the surveyed dwellings had confirmed, likely or possible damage equivalents.

Figure 3 shows the confirmed damage by building age class, compared with confirmed damage only in risk structures, those with confirmed damage plus damage that requires further investigation, and the presence of abnormal odour. All damage equivalents continued to be most common in older buildings. Buildings often had multiple types and likelihoods of damage where 'likely' damage was the most common, followed by 'possible' damage (Figure 4). Odours were present in 25% of houses with confirmed damage, and in only 4% of those without confirmed damage.

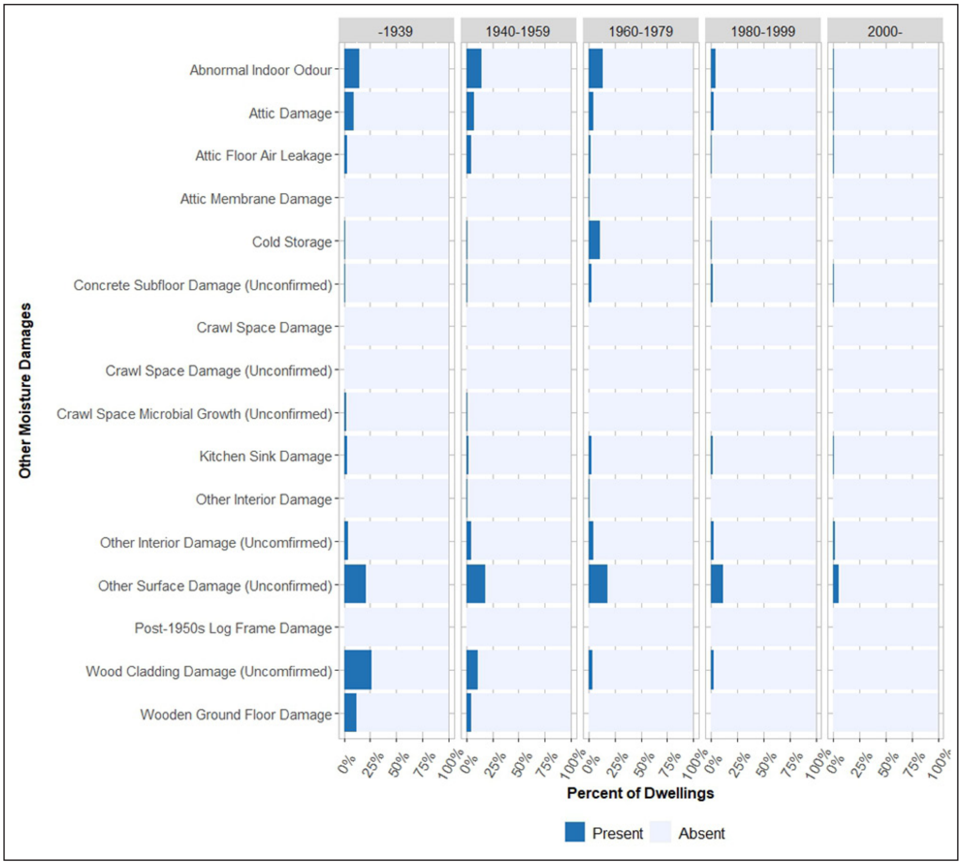


Figure 2: Percentage of houses by other identified damage in locations other than risk structures and by building age.

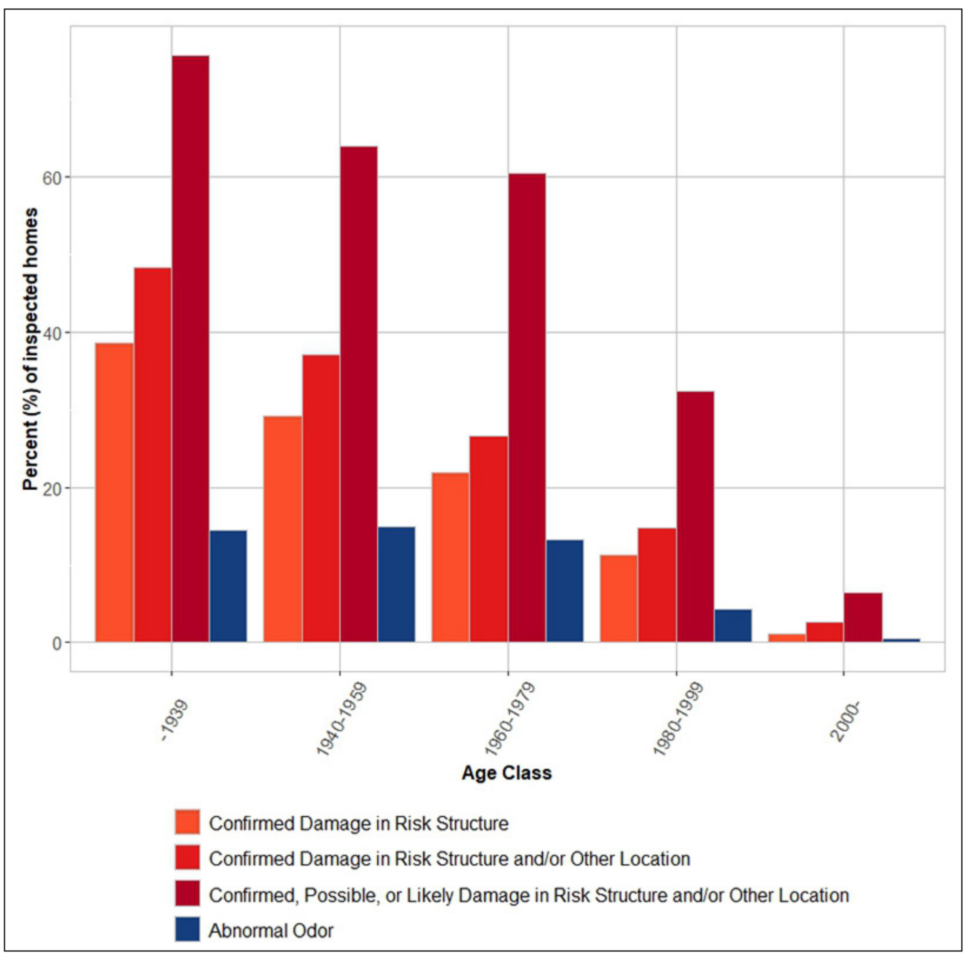


Figure 3: Comparison, by age class of the dwelling, of confirmed damage in a risk structure, confirmed damage in any location, confirmed damage, likely or possible damage, and odour.

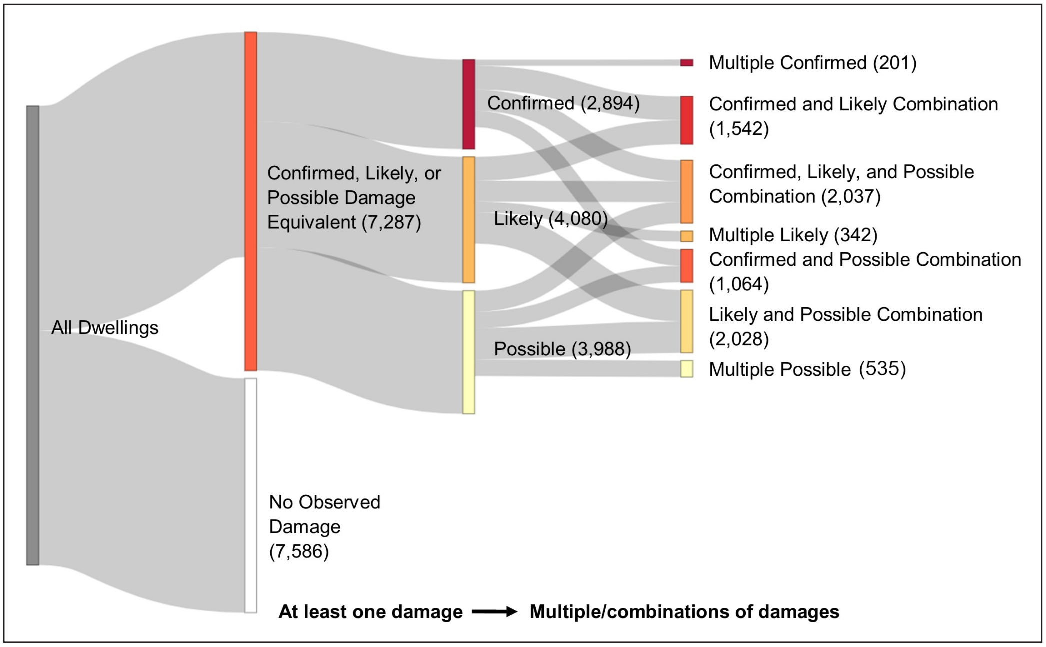


Figure 4: Prevalence of damaged risk structures and equivalents in surveyed dwellings from all dwellings (left) to those with at least one damage (middle) to those with multiple damage (right).

Note: Damage is classified according to damage likelihood (Table 2), with the right-hand side showing multiples of the same likelihood or combinations of different likelihoods.

3.3 MULTIVARIATE MODELLING

The risk of confirmed damage by housing and area characteristics was examined using logistic regression. The unadjusted (model 1) and age-adjusted (model 2), and fully adjusted (model 3) odds ratios are shown in Figure 5.

Unadjusted logistic regression (model 1) indicates building age is the greatest risk factor for confirmed damage. When building age was analysed as a continuous variable, an odds ratio of 1.037 (95% confidence interval (CI) = 1.036–1.038) per year, or 1.476 (95% CI = 1.446–1.505) for each decade since construction was observed up to 100 years old, after which the number of buildings became too few for reliable estimation. Other building characteristics crudely associated with increased risk include: detached buildings; those constructed in-place; wood ground floors or crawlspaces; log or wood external walls; wooden or boarding cladding; those with cellars; roofs that were not split ridged and with sheet metal roofing; and homes without mechanical input and output ventilation. Risk was also greatest in regions with the greatest amount of wind-driven precipitation and in lower income postcodes.

Adjusting the analyses for building age class (model 2) had a very large effect, reducing the estimated odds ratios of most variables to below 2. The main exception was having no designed ventilation system, but this was present only in 26 homes. With age adjustment, cladding type, income class and roof type were no longer significant risk factors. Risk continued to be present in detached homes, those built in-place, homes with attic floors that were absent or made out of non-stone materials, homes with wooden or log walls, those with cellars, homes without mechanical ventilation systems, and homes with fibreboard roofing. Wind-driven precipitation region also continued to be significant. Age-adjustment substantially reduced the risk from log walls in particular, but they continued to be at an increased risk in both pre- and post-1950 buildings. The effects of building and are characteristics explained around a third of the effect of building age, while the presence of risk structures explained 60% of the effect of age.

Using multiple logistic regression to adjust for all building characteristics (model 3) led to relatively small changes in the odds ratios compared with model 2. Age remained the dominant risk factor for confirmed damage, but the odds ratio per year of building age was reduced to 1.024 (95% CI = 1.021–1.026). Compared with model 2, monopitched, flat, and double-ridged roofs and three-storey buildings were the only building characteristics that showed a significant risk of moisture damage following complete adjustment that was otherwise insignificant when adjusting only for age. The highest income postcodes also showed a significant risk reduction compared with model 2 when adjusting for all variables.

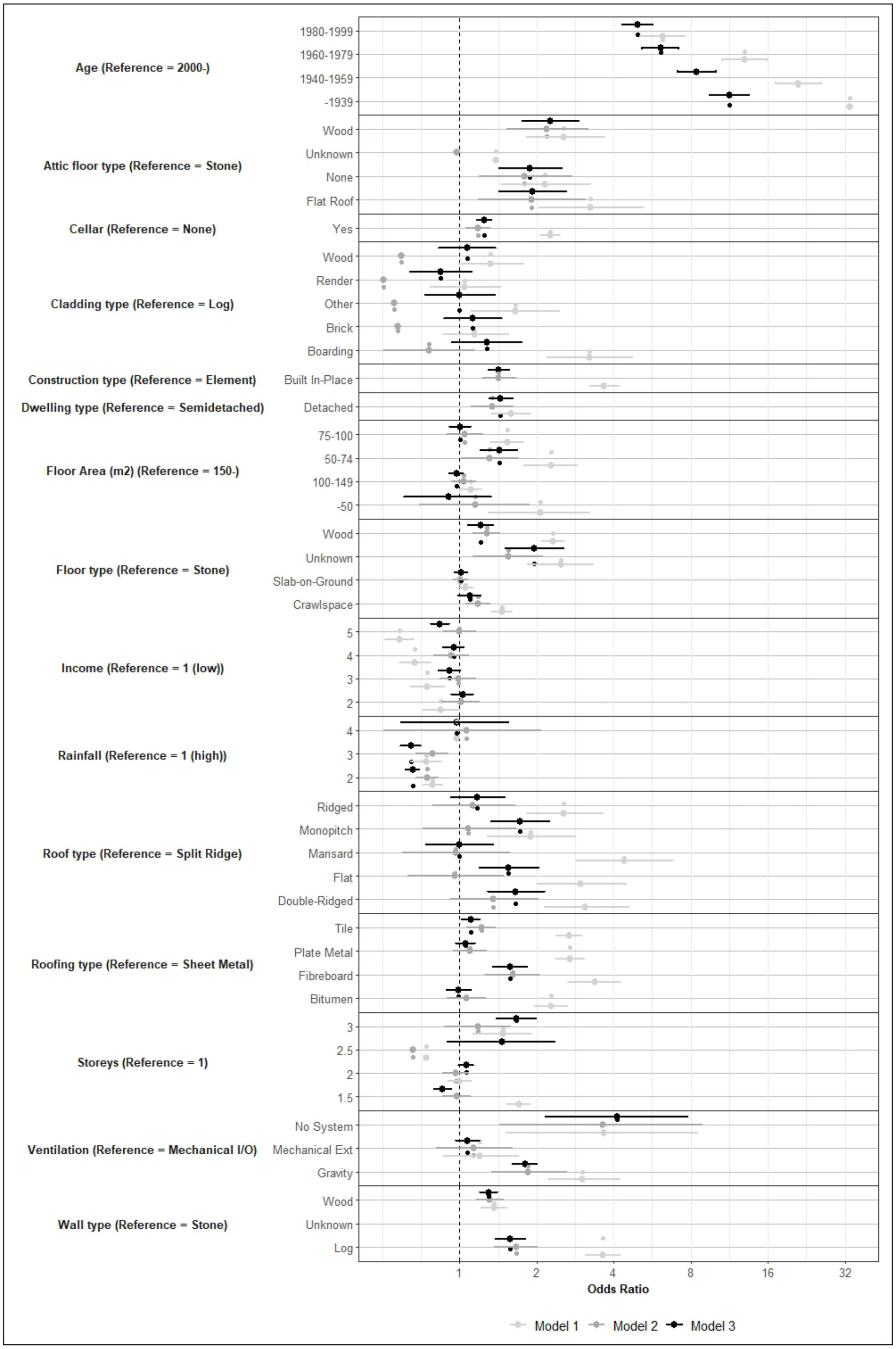
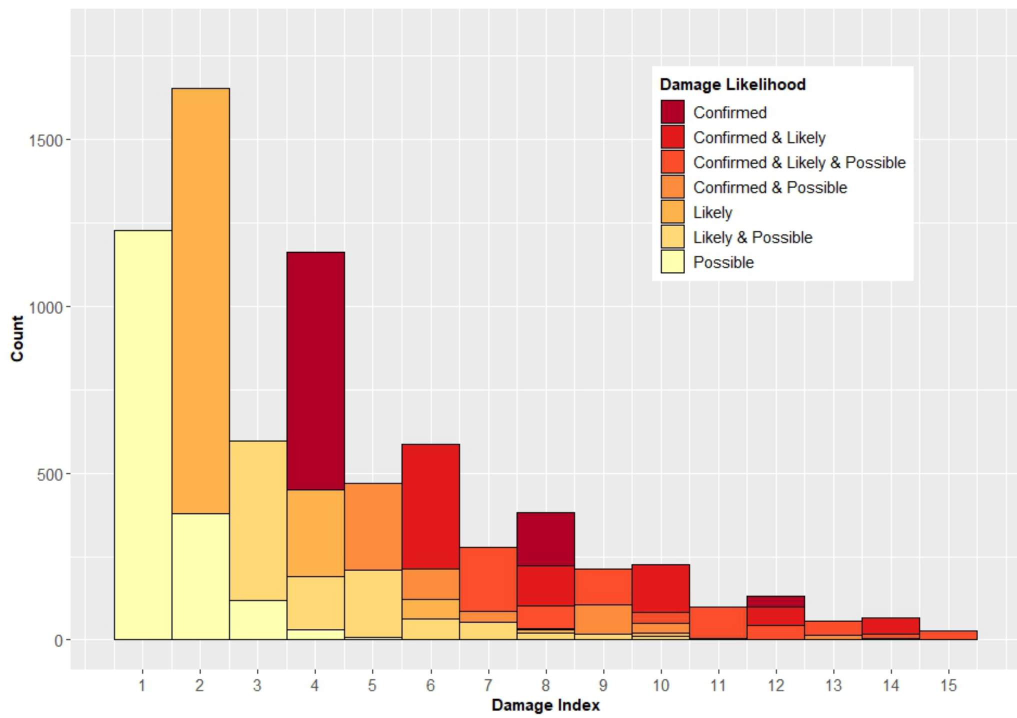


Figure 5: Odds ratios for confirmed damage in risk or other structures for model 1 (crude), model 2 (age adjusted) and model 3 (adjusted for all variables).

Note: Ranges represent 95% confidence intervals (CI).

3.3.1 Degree of moisture damage

The damage index represents the severity of damage in a house, combining confirmed damage, likely and possible damage in multiple locations. The maximum damage index was 30. However, this was truncated in the analysis at 15 due to the low number of dwellings above this level. The average damage index score is shown in Table 3, and around 51% of houses had a damage index equal to zero. Figure 6 shows the distribution of damage index scores (excluding homes with verified no damage), illustrating the increasing proportion of homes with multiple different damage likelihoods as the damage index increases. The table within Figure 6 shows how, as the damage index increases, the probability of a home having confirmed damage, or combinations including confirmed damage, also increases.



Damaged (%)	0	0	61	55	79	80	92	91	91	97	100	98	100	100
Opened (%)	77	80	36	43	84	89	57	59	87	98	75	74	91	88
Unopened (%)	23	100	16	100	26	100	23	100	33	100	33	100	27	72

Figure 6: Counts of the different houses (*y*-axis) by the damage index (*x*-axis), calculated by summing damage likelihood in homes (Table 2).

Note: Homes with verified no damage are excluded. Counts are stacked by the number of homes with different damage likelihoods or combinations thereof. To break this down further, the table shows—for each damage index—the probability that the homes have different damage likelihoods.

The results of the unadjusted (model 1), age-adjusted (model 2) and fully adjusted (model 3) ordinal logistic regression for the damage index is shown in Figure S2 in the supplemental data online. The age of the house continued to be the greatest dominant risk factor for the damage index in both unadjusted and fully adjusted ordinal models. The odds ratios observed for the damage index were very similar to those observed for the binary indicator of confirmed damage (see Figure S3 online). Key differences included comparatively higher odds for the index for homes with flat roofs and slightly higher estimates for the age of the building. The odds of having abnormal indoor odour detected was 1.39 for each unit increase in the damage index, indicating an association between the severity of damage and odour.

4. DISCUSSION

The study analyses moisture surveys for almost 15,000 Finnish dwellings that, uniquely, include investigations within specified risk structures. Confirmed damage was observed in 19% of investigated homes, the majority of which were found in risk structures (15% of investigated homes), and around 49% of the surveyed houses had either confirmed, likely or possible damage equivalent. The results for confirmed damage are lower than those from Nevalainen *et al.* (1998) carried out in the 1990s, who reported dampness in 52% of a sample of 310 Finnish houses, but similar in scale when likely or possible damage is also included. As in Nevalainen *et al.*, the present paper finds that the prevalence of moisture damage varied with construction characteristics common in buildings of different ages and likely due to material ageing.

Results show a wide variation in damage in different risk structures. Risk structures most likely to have verified moisture damage were walls in contact with soil (38.7%), pre-1950s log walls (29.6%), wooden ground floor above concrete slabs (22.8%) and low foundations (20.0%). Many of the same risk structures were found to have moisture damage in a study of 168 Finnish public buildings where the occupants had reported indoor air quality-associated health symptoms (Annila *et al.* 2018), including timber ground floors with a crawl space (85% damage), basement walls (56%), log walls (50%), flat roofs (30%) and ridge roofs (29%). The prevalence of damage in this paper is

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comparatively lower, possibly due to different inspection methods, different building types, and the above study being conducted in buildings with suspected moisture damage issues, and these prior studies missing post-2000 buildings where the least moisture damage was found in this paper.

Around 31% of homes had at least one other confirmed, likely or possible damage outside the risk structures. These were most commonly recorded as a general unconfirmed other surface damage. This indoor damage is similar in scale to the results from a study of visible dampness and mould in schools (Haverinen-Shaughnessy *et al.* 2012) (24%) and office buildings (Salonen *et al.* 2007) (44%) in Finland. It is comparatively less than a study that found visible dampness in 52% of surveyed homes in Finland (Koskinen *et al.* 1999), possibly due to the present study including newer buildings. Odours were present in 7% of surveyed houses, also more common in older houses. Around 10% of dwellings had multiple locations with confirmed damage.

The statistical analysis indicates the age of the house was the greatest determinant of confirmed damage and increasing damage index, with nearly half of all houses built pre-1939 having at least one confirmed damage in a risk structure. Adjusting for age, other characteristics associated with increased moisture risk include detached housing, housing constructed in-place, log walls, monopitch roofs, fibreboard roofing, attics with either no floor or a wooden floor, and gravitational or no designed ventilation system. A significantly increased risk of damage was seen in homes in areas with higher amounts of driving rain. The risk of confirmed damage and damage index was highest in lower income postcodes in the crude model, insignificant after adjustment for age but significant when adjusting for all variables. That suggests that lower income postcodes have greater numbers of older properties with construction characteristics that increase moisture damage risk. That may also mean potential socio-economic inequalities in exposure to moisture damage.

Building characteristics explained about a third of the effect of building age, and the presence of a risk structure around 60% reflecting the prevalence of different moisture risk structures common in different construction eras. They may also be due to older buildings having been damaged or exposed to environmental moisture for a longer period. Overall, the results suggest that the moisture damage situation in Finnish buildings has improved in newer buildings, with improved construction methods, the reduction of risk structures and mechanised ventilation systems ensuring a more reliable removal of damp indoor air. The risk factors for binary presence/absence of confirmed damage were similar to those of the damage index, indicating that these factors do not contribute to isolated moisture problems.

4.1 STRENGTHS AND LIMITATIONS

There are several limitations to this study. The survey is restricted to detached and semidetached houses, which account for around 41% of the 3,076,000 dwellings in Finland (Tilastokeskus 2022). Houses in the capital region, Uusimaa, are overrepresented in the data. Newer buildings are also overrepresented, with dwellings built post-2000 comprising 28% of the inspected buildings versus 20% of the Finnish stock of detached and semidetached properties. In contrast, those built pre-1939 comprise 12% of all buildings, but only 7% in the present dataset. However, the results are likely to give a reasonably good picture of the damage situation in detached and semidetached houses in Finland in general. A strength of the study is the large number of buildings with detailed survey and housing characteristics.

Moisture surveys are typically undertaken when the dwelling is bought or sold. Therefore, the data are likely biased toward those with home ownership or private rental properties, which represent the majority of homes in Finland (62% and 24% of dwellings, respectively; Tilastokeskus 2022). The types of homes included in the dataset, and the transaction types, mean the data were expected to be biased toward higher income households. The moisture survey is a service usually purchased by potential homebuyers and is almost always performed except in buildings with obvious damage that will be demolished. Therefore, this analysis may underestimate damage.

The survey itself relies mainly on a visual and odour inspection of various structures. A survey of public buildings has estimated that visual inspections can detect only about 70% of hidden mould (Annila & Lahdensivu 2020). While surveyors were able to drill holes to inspect inside risk

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structures if necessary, the number of holes is limited, or they may not be granted permission to drill holes. Some risk structures are harder to access than others. For example, double slabs are never opened; this complicates the comparisons of damage risk between risk structures.

The damage index is applied as a way of quantifying the degree of moisture damage within the houses, accounting for both damage classes and the number of locations of damage. This approach was employed because prior studies often use a binary presence or absence of mould or moisture as an indicator of exposure, but the extent and number of damage may be important for health outcomes. Therefore, it is necessary to develop a methodology to describe exposure (Mendell & Kumagai 2017; Mendell *et al.* 2018) that can be later linked to health outcome data to estimate dose–response. The damage index scores for the different damage classes and the structures included are informed by expert opinion, and further work is required to refine this method.

Despite these limitations, the dataset is, to our understanding, the best available source to estimate moisture damage prevalence in single-family homes in Finland. The large survey of homes allows for the estimate of damage risk according to various building characteristics, while the spatial information allows the data to be linked to neighbourhood income and precipitation data. A significant advantage of the data is that the survey includes both investigations inside risk structures and visible moisture damage elsewhere in the building. The data and analysis provide opportunities for future research, linking the dataset to occupant health records to examine potential associations between the presence of confirmed damage, the damage index and various health outcomes.

4.2 IMPLICATIONS

The cumulative economic impact of moisture damage in housing is significant. An estimated €450 million annually is spent on healthcare, pensions and loss of productivity due to the poor health outcomes in Finland (Reijula *et al.* 2012), and around €400 million on repairing moisture damage in residential buildings (Nippala & Vainio 2016). Actual repair costs fall short of the estimated costs of technical repairs and quality improvements needed to maintain the housing stock condition, estimated to be €9.4 billion over the period 2016–25 (Nippala & Vainio 2016); this is expected to increase to €11.1 billion from 2026 to 2035 because of the need to repair buildings built in the 1980s and the dominance of detached houses in residential buildings. The results of this study characterise the prevalence of moisture damage across different buildings and structures, which can help provide additional context for research on the economic or health consequences of moisture damage. Understanding the moisture damage prevalence in risk structures in buildings can also support targeted mass remediation efforts or incentives to households to repair these structures before damage occurs. Open data on housing age and construction characteristics can be used to identify areas with a high number of at-risk buildings (an example is provided in Figure 7), which could help with identifying homes for renovation or for public health campaigns.

These moisture challenges are set against a context of a changing climate. Projections indicate that in Finland winter precipitation will increase by 10% by 2050 under RCP4.5 and 17% under RCP8.5 relative to 1980–2010; by 2080, this increases to 14% and 28%, respectively (Ruosteenoja *et al.* 2016). Instances of heavy rainfall are projected to become more intense and frequent, and storm winds are expected to increase in much of the country. Additionally, the average relative humidity of outdoor air will increase, leading to slower drying of structures after precipitation, higher moisture content inside structures and increased failure rates in structures with inadequate building physical performance. Buildings in areas with the greatest driving precipitation are at increased risk of confirmed damage regardless of age, supporting the concerns about increased moisture damage throughout Finland as the climate changes. Therefore, it is critical that building facade and drainage research and regulations are developed to improve resilience to these changes, including areas that have not been historically exposed to high levels of driving precipitation but may in future. The proportion of damage in the risk structures vulnerable to precipitation, such as low foundation height or false plinths, may increase as the climate changes.

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The results suggest that modern Finnish building standards help reduce moisture damage levels, although this may change as the buildings age and climate changes. The Finnish housing stock is also changing to reduce its carbon footprint, and there is a need to increase the retrofit rate of existing buildings from the current rate of around 1.0–1.5% annually (Airaksinen *et al.* 2013). There is a risk that net zero technologies may aggravate moisture problems in buildings. The understanding of the moisture risk factors and structures in existing dwellings can help inform retrofit guidelines for dwellings. Finally, there is a need to minimise waste by extending the life cycle and adapting existing buildings (Huuhka & Kolkwitz 2021). Identifying and renovating problematic structures in older buildings before issues arise can help avoid demolition due to unrepairable damage.

Finland has a unique climate and construction practices compared with other countries, but there are potential international implications for this study. In many countries, timber construction is being promoted due to its relatively better environmental performance compared with other materials, and there is a need to improve the energy efficiency of housing whilst ensuring sufficient ventilation and reduced moisture risk. Finnish buildings are relatively energy efficient compared with the European Union average, have a large proportion of timber housing and modern buildings are almost entirely mechanically ventilated. This study highlights areas where issues may arise in such buildings, and the current Finnish building practices, which have reduced moisture risk, could inform regulation development and moisture guidelines in other locations. Results also show most homes with confirmed damage had damage within the building structure, demonstrating the importance of moisture surveys investigating within the building structure, particularly in colder climates.

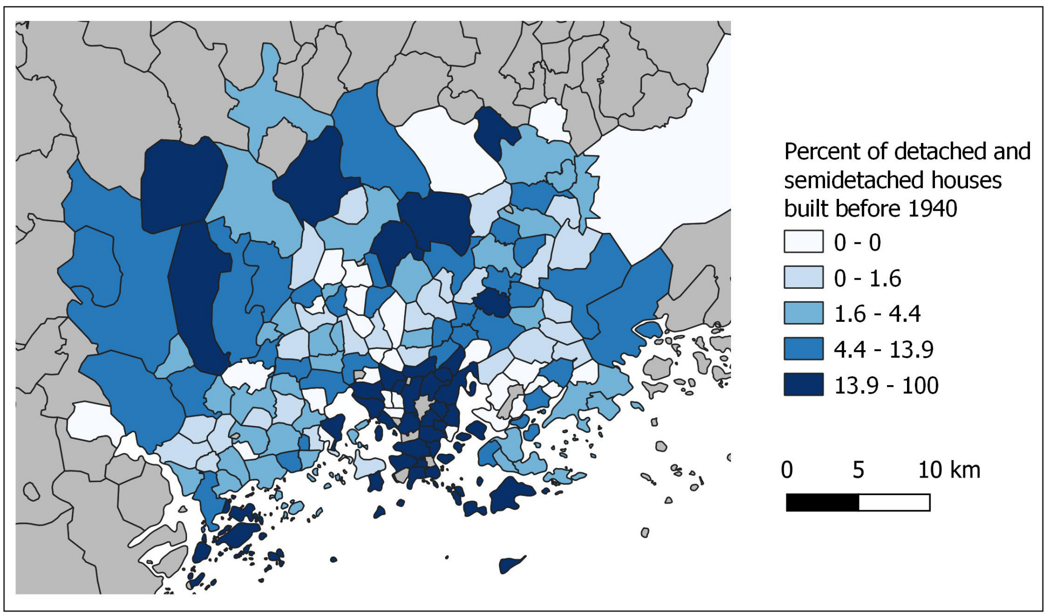

Figure 7: Data from Helsingin seudun ympäristöpalvelut (HSY) showing the percentage of single or semidetached homes built pre-1940.

5. CONCLUSIONS

Moisture damage in homes has significant health and economic implications. This paper sought to estimate the prevalence and extent of moisture damage in a large dataset of Finnish homes by analysing the risk of confirmed damage and increasing damage index score for different housing characteristics. Results show that 19% of homes had confirmed damage in the home, and 15% had damage in a risk structure. Multiple confirmed damage was found in around 10% of homes. Nearly half of the houses had confirmed, likely or possible damage. The age of the house was the greatest risk factor for confirmed damage, with the odds increasing by 1.48 each decade since construction, and nearly half of all houses built pre-1939 having at least one confirmed damage. Other risk factors included monopitch or flat roofs, log external walls, fibreboard roofs, attics with either no floor or a wooden floor, absence of mechanical ventilation systems, and exposure to wind-driven precipitation. The risk factors for the damage index were largely similar to those for confirmed damage. Results can be used to understand the risk factors for moisture damage better, derive estimates of exposure to moisture damage for dose–response studies, and develop ways to improve moisture management now and in the future.

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COMPETING INTERESTS

AH reports a relationship with Raksystems Oy that includes employment.

DATA AVAILABILITY

Data supporting this study cannot be made available due to commercial restrictions.

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SUPPLEMENTAL DATA

Supplemental data for this paper can be accessed at: https://doi.org/10.5334/bc.366.s1.

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