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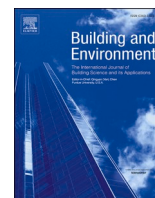
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Geographical and environmental contexts associated with mould contamination in dwellings in France

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ABSTRACT

Indoor visible mould is a widespread issue. Population-based studies on the impact of dwelling location on mould contamination are rare. We investigated the associations of geographical/environmental contexts with mould contamination in the French CONSTANCES cohort.

Participants reported presence of visible mould and mouldy area size (spots, $<0.2\text{m}^2$, $[0.2\text{--}1\text{m}^2]$, $1\text{--}3\text{m}^2$ or $>3\text{m}^2$) in the bathroom, kitchen, living room and bedroom. Dwelling mouldy area size was defined by the maximum area in one of the four rooms. Logistic models were used to study cross-sectional associations of urbanicity, size and type of functional urban area, climate typologies, temperature and precipitations with mould contamination, adjusting for potential confounders selected by directed acyclic graphs.

Analyses included 97,825 adults (51 years old, 54% women, 67% living in houses). Visible mould and mouldy area size $>0.2\text{m}^2$ were reported in 22% and 2.7% of dwellings, respectively. Living in cities ≥ 2000 inhabitants was inversely associated with visible mould (ORs between 0.81–0.91) than rural areas, except Paris. Altered and pure oceanic climates were positively associated with visible mould (reference: degraded oceanic). Annual average temperature, total precipitation, rainy days in January or July and flooded areas were positively associated with visible mould and mouldy area size, whereas number of days $<5^\circ\text{C}$ and thermal amplitude were inversely associated. Outside Paris, surrounding greenness was positively associated with visible mould, particularly for mouldy areas $<0.2\text{m}^2$.

These findings highlight the importance of considering multiple indicators. They support the need to account for geographical and environmental contexts when designing strategies to prevent and reduce mould contamination.

1. Introduction

Visible mould affects up to 33 % of dwellings in the United States, 25 % in Europe, and between 14 % and 22 % in France [1–3], highlighting its widespread occurrence and public health relevance. Moulds are ubiquitous aerobic fungi [4], that can easily enter indoor spaces via occupants, pets, or ventilation systems, subsequently colonising a wide range of ecological niches within all kinds of buildings [5]. Fungal growth is influenced by multiple environmental parameters. Indeed,

biotic factors include the viability of spores, the specific fungal species present, and competitive interactions between fungi and other microorganisms [6]. Abiotic, physical, and chemical factors include pH, oxygen, light, temperature, nutrient availability, and moisture [7]. These factors are difficult to study and control due to their complex, multifactorial, and often interdependent nature.

Indoor environments typically provide abundant oxygen and nutrients, and favourable temperatures, and moisture is often the key limiting factor for spore germination and mould growth [8]. Sources of indoor

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moisture are diverse and may arise from discrete events, such as weather incidents, flooding or water damage, from everyday activities such as breathing, showering, or cooking, or from synergistic effects involving interrelated factors [9] such as structural deficiencies in buildings, residents' socio-economic conditions, ventilation practices, and geographic location.

To our knowledge, few studies worldwide have specifically investigated the influence of dwelling location on mould occurrence and the resulting impacts [10,11]. Furthermore, comparisons between studies are challenging, as research often involves different countries or regions and geographical/environmental characteristics, small sample sizes, and non-standardised protocols for assessing mould contamination in dwellings. Research in this field has adopted three complementary approaches: examining the spatial distribution of fungal contamination within a given territory [12], assessing the distribution of fungal species [13], or studying the presence of moulds across different types of environments—urban, peri-urban, and agricultural [14].

Our aim was to map and analyse the spatial distribution of various dwelling characteristics and the presence or absence of visible mould in French dwellings. We then investigated the association of presence of visible mould and mouldy area size with the geographical and environmental context of the dwelling location, including three indicators of urbanisation: urbanicity, and the size and type of the functional urban area.

2. Methods

2.1. Design

CONSTANCES is a population-based cohort designed as a sample of the French adults [15]. Between February 2012 and December 2020, participants aged 18–69 years were randomly selected among beneficiaries of the main national health insurance, covering around 85 % of the population [16]. At inclusion, all participants ($n = 220,000$) completed several self-administered questionnaires, and attended one of the 24 participating Health Prevention Centres (HPCs) located in 21 départements (a French administrative unit) throughout metropolitan France for a comprehensive health examination and a medical questionnaire [16]. Subsequently, participants were invited to complete self-administered annual follow-up questionnaires, either in paper form or online, which in 2019 included a series of questions about their dwelling, including the presence of mould, and to undergo a new health examination every 4–5 years [17]. In addition, home addresses have been recorded and geocoded since inclusion for all participants, including their moves.

The authors certify that all procedures performed in the study complied with the ethical standards of the relevant national and institutional committees on human experimentation and with the 1975 Declaration of Helsinki, as revised in 2008. All procedures were approved by the Institutional review board (IRB) of the National institute of health and medical research (Inserm) (Opinions No. 01–011 and No. 21–842), and authorized by the French data protection authority (Commission nationale de l'informatique et des libertés, CNIL) (Authorization No. 910,486). The biobank received a favorable opinion from the Research ethics committee (Comité de protection des personnes) (CPP Sud Est I, Opinions No. 2018–32) and was authorized by the CNIL (Authorization No. DR-2–2018–137). All volunteers signed written informed consent for their participation in the Constances cohort, and when applicable, for inclusion in the biobank (ethical approvals, authorizations, and consent procedures are available under the “*Rights and data protection*” section of the Constances website).

2.2. Study population

The study population included participants who fulfilled the 2019 questionnaire and lived in a house or flat in metropolitan France. Those

reporting living in dwellings under 9 m²—the legal minimum in France [18]—were excluded. In the absence of standard thresholds for upper outliers, we applied a priori cut-offs at the top 0.01 % of the distribution: thus, participants who reported living in dwellings over 950 m² or with more than 13 occupants were excluded. Participants with missing data on visible mould were also excluded.

2.3. Mould contamination assessment and dwelling characteristics

Participants reported both the presence of visible mould and the mouldy area size in the bathroom, kitchen, living room and bedroom. For each room, the mouldy area size was assessed by the participants using illustrations provided in the questionnaire: 0.2 m² corresponding to 3 A4 paper sheets and 1 m² to half a door. Mouldy area size was expressed in six categories: 0 m², spots, <0.2 m², [0.2 m²–1 m²], [1 m²–3 m²] or >3 m². As previously done [12], the maximum reported mouldy area size across the four rooms was considered. Due to small numbers in the higher categories, these six categories were then grouped into three: no mould (0 m²), <0.2 m², and ≥0.2 m².

As participants responded to the questionnaire along the year, and season can contribute to the variability of indoor total airborne fungal concentrations [19], the response period was categorised into two seasons: warm (March to September) and cold (October to February) [20]. Dwelling characteristics, *i.e.*, dwelling type (house or flat), dwelling's surface area, number of occupants, heating difficulties and presence of ventilation system were recorded (see supplementary methods for further details). The ratio between the number of occupants and the dwelling's surface area was calculated, referred to as “occupant-surface ratio” hereafter and expressed as number of occupants per 100 m². The age of the dwelling was estimated using 2019 data from the French National Institute for Statistics and Economic Studies (INSEE), following INSEE's standard classification which distinguishes buildings constructed up to 1970 from those built from 1971 onwards [21], a cutoff reflecting key changes in construction practices [22]. For participants living in flats, if their IRIS (Ilots Regroupés pour l'Information Statistique) area had more than 50 % of flats built up to 1970, the dwelling was classified as built up to 1970; otherwise, it was considered built from 1971 onwards. The same approach was applied for those living in houses.

2.4. Geographical and environmental contexts assessment

Several variables were used to describe the geographical and environmental characteristics of the dwellings, all assigned at the IRIS level.

The neighbourhood socioeconomic deprivation level was evaluated by the contextual French Deprivation Index (FDep) from 2015, expressed into five quintiles from the least (Q1) to the most (Q5) deprived [23].

Urbanicity was defined using the urban unit classification developed by INSEE, which considers a group of municipalities where no building is separated from the next by more than 200 m and categorised into five levels: rural municipalities, urban municipalities with 2000 to 9999 inhabitants, urban municipalities with 10,000 to 99,999 inhabitants, urban municipalities with more than 99,999 inhabitants (excluding Paris), and the Paris metropolitan area.

The Functional Urban Area (FUA) classification was also used to account for patterns of urban development and commuting flows of municipalities through two indicators: i) the size classified into FUAs with fewer than 50,000 inhabitants; 50,000 to 199,999 inhabitants; 200,000 to 699,999 inhabitants; 700,000 inhabitants or more (excluding Paris); and the Paris area; ii) and the role within the urban hierarchy categorised as municipalities outside of FUAs, commuting area; secondary centre; other municipality in the principal centre and central municipality [24].

Climatic conditions were assessed through both typological and continuous indicators. Climatic typology was derived from the

classification proposed by Joly *et al.* distinguishing six major types: degraded oceanic (plains of central and northern France, reference category), mountain and mountain margins, altered oceanic, pure oceanic, southwest basin, and Mediterranean climate [25]. Continuous indicators were based on long-term monthly averages calculated for the 1971–2000 period, corresponding to the standardized climatological normal used to characterize climate, and not short-term meteorological variations. These included annual average temperature, annual number of days below $-5\text{ }^{\circ}\text{C}$, annual number of days above $30\text{ }^{\circ}\text{C}$, annual thermal amplitude, total annual precipitation, and the number of rainy days in January and in July. The use of January and July values as seasonal markers was intended to reflect meaningful climatic contrasts between winter and summer. January is the coldest month for 98 % of meteorological stations in France, while July is the warmest for 56 % of stations, slightly ahead of August (44 %) [25]. These seasonal indicators help to capture the regional variability in rainfall patterns and temperature extremes across metropolitan France.

Flood exposure was captured through a binary indicator reflecting the presence of at least one episode of flooding or rising waters in the dwelling, defined using municipalities declared natural disaster zones for flooding in 2018 and 2019 [26].

Finally, to estimate residential surrounding greenness, we used satellite imagery to derive Normalised Difference Vegetation Index (NDVI) - a unitless indicator of vegetation density, based on light absorption and reflection by chlorophyll [27]. Here, as in several other former studies (*e.g.*, [28]), we extracted data from Landsat-8 using Google Earth Engine, with a $30 \times 30\text{ m}$ spatial resolution, computing the greenest NDVI value between May and July from 2013 to 2020 on each pixel, to account for the greenest months in mainland France over this period. NDVI values range from -1 to $+1$, but only positive values represent vegetated areas, with higher values indicating denser green vegetation; negative values indicate non-vegetated surfaces such as water or snow, and null values indicate bare soil or built environments. Therefore, we converted negative NDVI values to null before calculating mean NDVI values within 100-metres and 300-metres buffer sizes around each residential address.

2.5. Mapping

Maps were drawn on QGIS software (version 3.34.12-Prizren). The distribution of CONSTANCES participants at the IRIS level was mapped, the smallest statistical unit used in metropolitan France. The flat-to-house ratio was also mapped followed by the percentage of dwellings with visible mould, the mean occupant-surface ratio, the percentage of dwellings with heating difficulties, and the absence of a ventilation system—first for all dwellings combined, and then stratified by dwelling type. These housing indicators were represented across functional urban areas with at least 30 participants, with all areas illustrated in Fig. S1, highlighting those included in the analysis.

2.6. Statistical methods

Comparisons of the characteristics of the participants and the dwellings according to dwelling type (house or flat) were carried out using Chi-square test for categorical variables and Student's *t*-test for continuous variables. Analyses also included comparisons of geographical and environmental contexts, stratified by dwelling type. Cross-sectional associations of urbanicity, functional urban area size and type, climate typology, temperature and precipitation indicators, flooded areas, and residential surrounding greenness (NDVI) within 100 m with the presence of visible mould or maximum of mouldy area size were estimated by binary logistic or non-ordinal polytomous logistic regressions ("no mould" being the reference group). The variables included in the models were selected based on assumptions formalised using directed acyclic graphs (DAGs) constructed with DAGitty (Fig. S2). Estimates were calculated per unit increase for the following continuous

environmental characteristics: annual average temperature and annual thermal amplitude ($\uparrow 10\text{ }^{\circ}\text{C}$); number of days below $-5\text{ }^{\circ}\text{C}$, above $30\text{ }^{\circ}\text{C}$, and rainy days in January and July ($\uparrow 5$ days); total annual precipitation ($\uparrow 500\text{ mm}$); and NDVI per one interquartile range (IQR).

Due to high correlations between some of the climatic parameters (Fig. S3), each parameter was analysed in a separate model. First, we performed univariate analyses and then multivariate analyses with several levels of adjustments: i) first adjusting for FDep, ii) then further adjusting for occupant-surface ratio to also consider the density of occupancy, which is a determinant of mould contamination [12] and iii) to account for potential confounding between temperature and precipitation, models including temperature-related indicators were additionally adjusted for total annual precipitation, and those including precipitation-related indicators were adjusted for mean annual temperature. For urbanicity and functional urban area-size/type, the occupant-surface ratio was not included in the models due to its potential role as a mediator. Stratified analyses by dwelling type were conducted to address the specificity of each dwelling type, and tested for interactions by including an interaction term in the regression models. For interaction tests, a Bonferroni corrected significance *p*-value threshold for 26 comparisons ($p\text{-value} = 0.05/26 = 0.0019$) was applied to account for multiple comparisons [29]. Additional adjustments for presence of ventilation system, response period or age of dwelling were performed to account for potential residual confounding.

The association between flooded areas and mould contamination was assessed only among participants living in houses and in ground-floor flats, where the impact of flooding or rising water is expected to be more directly observable.

Sensitivity analyses were performed. Given that the geocoding precision ranged from exact address to postal code centroid, analyses were conducted by restricting the main model to participants for whom exposures were matched at the exact address or street segment level, to minimize potential misclassification for all exposure variables. For NDVI, additional analyses were conducted using 300-metres buffer zones instead of 100-metres ones, and were stratified by degree of urbanisation (rural, urban, and Paris) to account for different structural conditions, and the specific characteristics of Paris including its dense built environment and low NDVI levels even near green spaces [30]. To further explore the influence of Paris-specific conditions, the analysis was restricted to participants living outside Paris.

Statistical analyses were performed using SAS version 9.4 (SAS Institute, Inc, Cary, NC). All tests were two-sided and considered significant at the 0.05 level.

3. Results

3.1. Description of geographical and environmental contexts, and of dwelling characteristics

The 2019 annual follow-up questionnaire was completed by 119,366 of participants (Fig. 1). Modest but significant differences were observed when comparing our study population ($n = 97,825$) to the 21,541 respondents to the 2019 questionnaire not included in the analyses regarding age, sex, educational level and dwelling type (Table S1).

Participants included in the analyses were on average 51.4 years old (SD: 13.4), 53.8 % were women and 66.6 % lived in houses (Table 1). Participants mainly lived in the IRIS units in or near one of the 24 participating Health Prevention Centres (Fig. 2). Most of them lived in urban areas, with 43.2 % residing in cities of over 99,999 inhabitants, and 15.8 % in Paris and its suburbs (Table 1). Considering functional urban areas size, 32.5 % lived in cities with over 700,000 inhabitants (excluding Paris) and 16.1 % in the Paris metropolitan area. Most participants (43.4 %) lived in commuting area municipalities, followed by 35.9 % in central municipalities. Regarding climate typology, 40.0 % lived in an altered oceanic climate, whereas 21.3 % were in a degraded oceanic climate. The annual average (arithmetic mean) temperature was

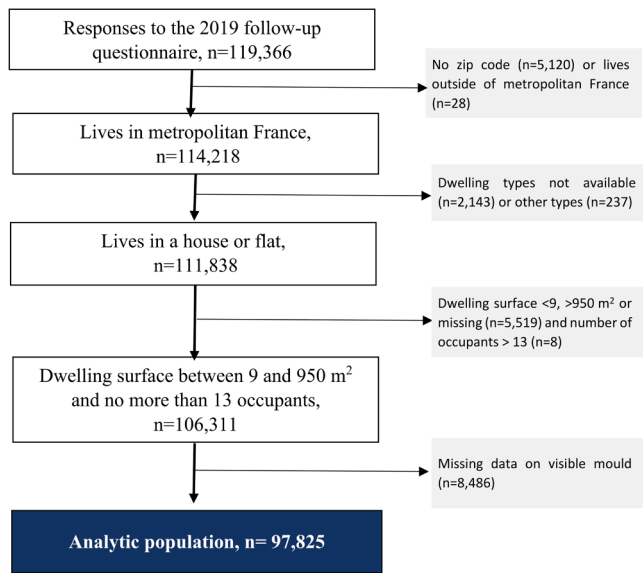


Fig. 1. Flowchart.

11.9 °C, with an annual temperature amplitude of 15.0 °C. On average, there were 2.5 days per year with temperatures below −5 °C and 5.9 days above 30 °C. Precipitation averaged 763.1 mm annually, with 10.8 days of precipitation in January and 7.0 days in July. The median NDVI was 0.69 (IQR: 0.56–0.78) and 0.72 (IQR: 0.58–0.80) in the 100- and 300-metres buffer zones, respectively.

The flat-to-house ratio was particularly high (>2) in the functional urban area of Paris and very low (<0.5) in 90.9 % of functional urban areas corresponding to participants’ addresses (Fig. S4). The mean occupant-surface ratio was 2.4 occupants per 100 m² (Table 1). Paris functional urban area had among the highest mean occupant-surface ratio (Fig. S5). Heating difficulties and the absence of a ventilation system were reported by 14.3 % and 12.7 % of participants, respectively (Table 1). The percentages of heating difficulties and dwellings without a ventilation system showed similar geographical patterns (Figs. S6–S7). The lowest rates were observed in western France, while the highest were generally found in the Paris region, as well as in south-eastern, northern, and, to a lesser extent, eastern France. The same overall patterns were observed when stratifying by dwelling type, although slight variations were observed. Visible mould was reported in 22.5 % of the dwellings, and mouldy areas ≥0.2 m² in 2.7 % (Table 1). The percentage of dwellings with visible mould was the highest in Paris functional urban area, and high rates were also observed in the smallest functional urban areas, particularly across western and south-eastern France (Fig. 3).

3.2. Associations between geographical contexts and the presence of visible mould

Fig. 4 shows the associations between geographical contexts and the risk of visible mould compared to no mould. Compared with rural municipalities, living in municipalities with 2000 or more inhabitants was associated with a lower likelihood of visible mould (OR ranging from 0.84 to 0.94; Fig. 4, Table S2), but this association attenuated as urban density increased and reversed in Paris and its suburbs (OR=1.43). The risk differed significantly according to dwelling type (p-interaction=0.0006). Both the size and the type of functional urban areas were also associated with visible mould. Compared to living in municipalities outside functional urban areas, living in Paris functional urban area was associated with a higher likelihood of visible mould (OR=1.47), whereas, living in functional urban areas with fewer than 50,000 inhabitants was associated with a lower likelihood (OR=0.89). Living in commuting area, secondary centre and central municipality

Table 1 Description according to dwelling type.

	All (n = 97,825)	Houses (n = 65,179)	Flats (n = 32,646)	p
Building before 1971	36,009 (36.9)	18,313 (28.2)	17,696 (54.3)	<0.0001
French deprivation index n (%)				<0.0001
Q1 (least deprived)	19,524 (20.0)	5275 (8.1)	14,249 (43.7)	
Q2	19,534 (20.0)	13,035 (20.0)	6499 (19.9)	
Q3	19,537 (20.0)	15,191 (23.4)	4346 (13.3)	
Q4	19,548 (20.0)	16,102 (24.8)	3446 (10.6)	
Q5 (most deprived)	19,512 (20.0)	15,435 (23.7)	4077 (12.5)	
Urbanicity, n (%)				<0.0001
Rural	17,167 (17.6)	16,479 (25.3)	688 (2.1)	
2000 to 9999 inhabitants	11,691 (12.0)	10,796 (16.6)	895 (2.7)	
10,000 to 99,999 inhabitants	11,138 (11.4)	9393 (14.4)	1745 (5.3)	
>99,999 inhabitants	42,243 (43.2)	27,770 (42.7)	14,473 (44.4)	
Paris and suburbs	15,488 (15.8)	661 (1.0)	14,827 (45.4)	
Functional urban area - size, n (%)				<0.0001
Outside functional areas	4162 (4.3)	3943 (6.1)	219 (0.7)	
< 50,000 inhabitants	6888 (7.0)	6221 (9.6)	667 (2.0)	
50,000 to 199,999 inhabitants	9975 (10.2)	8833 (13.6)	1142 (3.5)	
200,000 to 699,999 inhabitants	29,284 (30.0)	23,859 (36.7)	5425 (16.6)	
≥ 700,000 inhabitants (excluding Paris)	31,714 (32.5)	21,397 (32.9)	10,317 (31.6)	
Paris area	15,704 (16.1)	846 (1.3)	14,858 (45.5)	
Functional urban area - type, n (%)				<0.0001
Outside functional areas	4162 (4.3)	3943 (6.1)	219 (0.7)	
Commuting area	42,438 (43.4)	39,308 (60.4)	3130 (9.6)	
Secondary centre	451 (0.5)	218 (0.3)	233 (0.7)	
Other principal centre	15,544 (15.9)	10,518 (16.2)	5026 (15.4)	
Central	35,132 (35.9)	11,112 (17.1)	24,020 (73.6)	
Climate typology, n (%)				<0.0001
Degraded oceanic	20,807 (21.3)	16,282 (25.0)	4525 (13.9)	
Mountain and mountain margins	7849 (8.0)	6448 (9.9)	1401 (4.3)	
Altered oceanic	39,089 (40.0)	20,277 (31.2)	18,812 (57.7)	
Pure oceanic	13,459 (13.8)	11,532 (17.7)	1927 (5.9)	
Southwest Basin	8378 (8.6)	4753 (7.3)	3625 (11.1)	
Mediterranean	8100 (8.3)	5768 (8.9)	2332 (7.1)	
Annual average temperature, mean (SD)	11.9 (1.2)	11.8 (1.3)	12.2 (1.1)	<0.0001
Number of days below −5 °C, mean (SD)	2.5 (1.5)	2.6 (1.6)	2.2 (1.4)	<0.0001
Number of days above 30 °C, mean (SD)	5.9 (3.7)	5.7 (3.9)	6.2 (3.1)	<0.0001

(continued on next page)

Table 1 (continued)

	All (n = 97,825)	Houses (n = 65,179)	Flats (n = 32,646)	p
Annual thermal amplitude, mean (SD)	15.0 (1.7)	14.8 (1.8)	15.6 (1.4)	<0.0001
Total annual precipitation, mean (SD)	763.1 (153.3)	792.3 (154.2)	704.9 (133.6)	<0.0001
Rainy days in January, mean (SD)	10.8 (1.9)	11.1 (1.9)	10.2 (1.6)	<0.0001
Rainy days in July, mean (SD)	7.0 (1.7)	6.9 (1.7)	7.0 (1.7)	<0.0001
Flooded areas, n (%)	18,143 (18.5)	13,302 (20.4)	4841 (14.8)	<0.0001
NDVI (100m-buffer), median (IQR)	0.69 (0.56–0.78)	0.73 (0.65–0.80)	0.54 (0.43–0.66)	<0.0001
NDVI (300m-buffer), median (IQR)	0.72 (0.58–0.80)	0.77 (0.69–0.83)	0.54 (0.45–0.66)	<0.0001
Occupant-surface ratio, median (IQR)*	2.44 (1.67–3.33)	2.14 (1.54–3.08)	3.03 (2.11–4.29)	<0.0001
Heating difficulties, n (%)	13,828 (14.3)	8356 (13.0)	5472 (17.0)	<0.0001
Presence of ventilation system, n (%)	83,932 (87.3)	56,556 (87.8)	27,376 (86.4)	<0.0001
Water damage, n (%)	23,020 (24.6)	11,195 (17.7)	11,825 (39.2)	<0.0001
Signs of dampness, n (%)	27,121 (28.5)	16,787 (26.6)	10,334 (32.5)	<0.0001
Mouldy odour, n (%)	2255 (2.4)	1293 (2.0)	962 (3.0)	<0.0001
Visible mould in dwelling, n (%)	21,974 (22.5)	13,651 (20.9)	8323 (25.5)	<0.0001
Max of mouldy area size in dwelling, n (%)				<0.0001
No mould	75,851 (77.5)	51,528 (79.1)	24,323 (74.5)	
Spots	12,936 (13.2)	8191 (12.6)	4745 (14.5)	
<0.2 m ²	6417 (6.6)	3991 (6.1)	2426 (7.4)	
[0.2 m ² –1 m ²]	1596 (1.6)	910 (1.4)	686 (2.1)	
[1 m ² –3 m ²]	694 (0.7)	373 (0.6)	321 (1.0)	
> 3 m ²	331 (0.3)	186 (0.3)	145 (0.4)	

* Number of occupants per 100 m², SD: Standard deviation, IQR: interquartile range. Thermal amplitude: min–max temperature range.

was associated with a lower likelihood of visible mould (ORs: 0.81, 0.80, and 0.90 respectively), and the association with secondary centre was more marked in flats than in houses (p-interaction=0.0003).

Results were overall consistent after further adjustments for presence of ventilation system, response period or age of dwelling (Table S3).

3.3. Associations between environmental contexts and the presence of visible mould

Fig. 5 shows the associations between environmental contexts and the risk of visible mould compared to no mould. The type of climate was significantly associated with visible mould (Fig. 5, Table S4). Compared to the degraded oceanic climate, living in altered oceanic and pure oceanic climates regions were significantly associated with a higher likelihood of visible mould (ORs: 1.11 and 1.19, respectively). This association was more marked in flats, where the ORs reached 1.23 and 1.33, respectively (p-interaction<0.0001).

Most of climatic parameters showed significant associations with visible mould, with odds ratios ranging from 0.67 to 1.33. Annual average temperature was positively associated with visible mould, particularly in houses (p-interaction=0.0008). The number of days with a temperature below –5 °C was inversely associated with visible mould.

Significant association was observed between the number of days with temperatures above 30 °C and visible mould only after stratification by dwelling type (p-interaction<0.0001), with increased likelihood in houses and decreased likelihood in flats. Annual thermal amplitude was inversely associated with visible mould. Total annual precipitation and number of rainy days in January or in July were positively associated with visible mould with ORs of 1.11, 1.29 and 1.18, respectively. An effect of annual precipitation was observed for houses but not for flats; however, this difference was not statistically significant. The positive association with the number of rainy days in July was more marked in flats than in houses (p-interaction=0.0004). Among participants living in houses or ground-floor flats, living in an area affected by at least one flood or episode of rising water was positively associated with visible mould with an OR of 1.11. The association between residential surrounding greenness and visible mould differed by dwelling type, with an increased likelihood in houses (OR: 1.07 [1.03–1.11]) and a decreased likelihood in flats (OR: 0.93 [0.89–0.97], p-interaction<0.0001). Results were overall consistent after further adjustments for presence of ventilation system, response period or age of the dwelling (Table S5), or when restricting the analyses to participants with exact IRIS-level geocoding (Table S6). Computing mean NDVI within 300 m instead of within 100 m did not change our estimates (Table S7). Stratifying by degree of urbanisation (rural, urban, and Paris) showed contrasting associations between residential surrounding greenness and visible mould, with higher likelihood in rural and lower likelihood in Paris (p-interaction<0.0001, Table S7). Restricting the analyses to participants living outside Paris, residential surrounding greenness was positively associated with visible mould and no statistically significant heterogeneity was observed according to dwelling type (Table S8).

3.4. Associations of geographical and environmental contexts with mouldy area size

Tables 2 and 3 show the associations of geographical and environmental contexts with the risk of small or large mouldy areas compared to no mould. Associations with geographical contexts were overall more marked for larger mouldy area size ≥ 0.2 m² (Tables 2 and S9). The association observed in Paris and its suburbs was more marked for larger mouldy areas, with an OR of 1.80, compared to an OR of 1.38 for smaller areas. Compared to areas outside functional urban areas, participants living in functional urban areas with fewer than 50,000 inhabitants had lower likelihood of reporting mouldy areas ≥ 0.2 m² (OR=0.76) than smaller ones (OR=0.92). Similar patterns were observed for functional urban areas with 50,000 to 199,999 inhabitants (OR=0.69 vs. 0.97). In terms of functional urban area type, the likelihood of having a mouldy area ≥ 0.2 m² were lower in commuting area (OR=0.66) and secondary centre (OR=0.65) compared to areas outside functional urban areas. Living in central municipality was associated with lower likelihood of having mouldy area size <0.2 m² (OR=0.88).

Associations with environmental contexts were overall more marked for larger mouldy areas, i.e., ≥ 0.2 m² (Tables 3 and S10).

Regarding the type of climate, compared to the degraded oceanic climate, altered oceanic, pure oceanic, and mediterranean climates were associated with increased likelihood of having a large mouldy area (ORs of 1.23, 1.37 and 1.26, respectively). These associations were less marked for smaller area (ORs of 1.09, 1.16 and 1.01, respectively).

Regarding meteorology, annual average temperature, total annual precipitation, and the number of rainy days in January or July were positively associated with mouldy area size, with more marked associations observed for larger areas. Conversely, colder conditions were inversely associated with mouldy area size. An increase in the number of days below –5 °C and greater thermal amplitude were associated with lower risk of mouldy area size <0.2 m² (ORs of 0.80 and 0.68, respectively), and even more marked with larger mouldy areas (ORs of 0.60 and 0.62, respectively). Number of days above 30 °C was positively associated with mouldy area size ≥ 0.2 m² in houses, and inversely

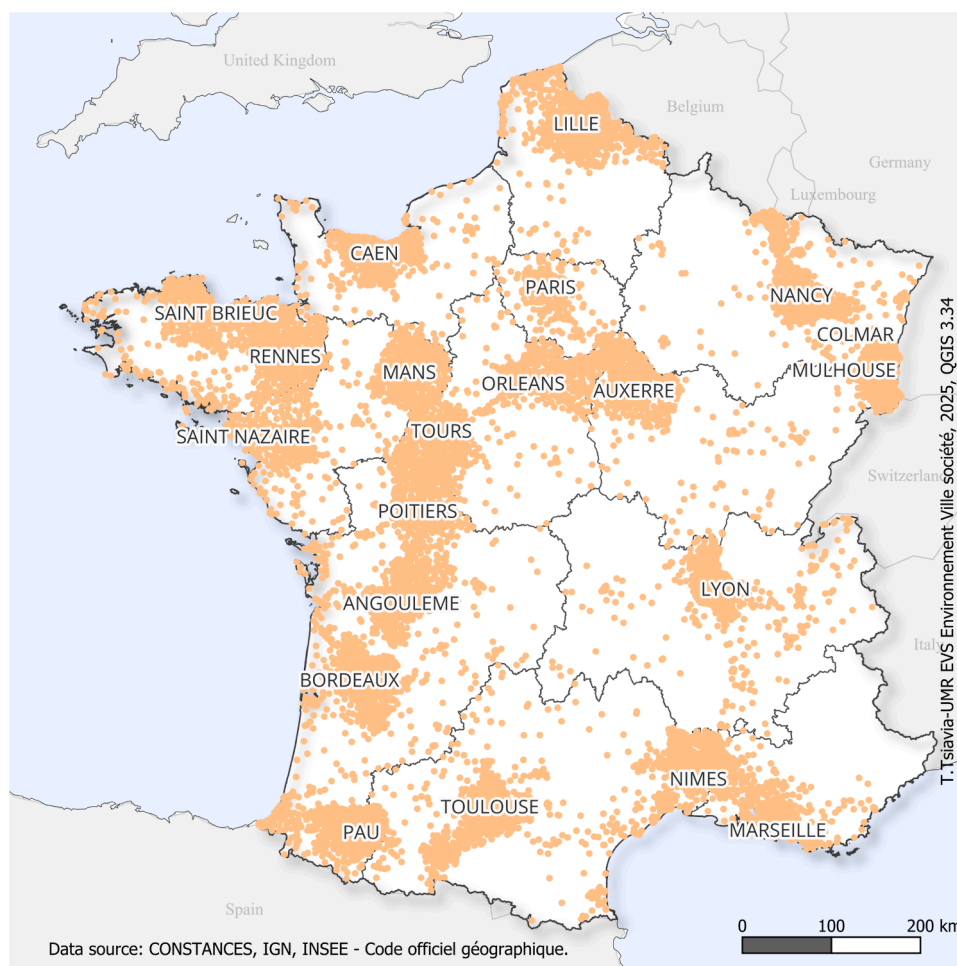


Fig. 2. Distribution of participants by IRIS units.

associated in flats, regardless of mouldy area size (p -interaction < 0.0001 , Table S10). Living in flooded areas was associated with a higher likelihood of mouldy areas size $< 0.2 \text{ m}^2$ (OR = 1.11). Results were overall consistent when restricting the analyses to participants with exact IRIS-level geocoding (Table S6).

Regarding residential surrounding greenness, no significant association was observed for mouldy areas. Residential surrounding greenness was positively associated with mouldy area size $< 0.2 \text{ m}^2$ in houses and inversely associated in flats (p -interaction < 0.0001 , Table S10). Computing mean NDVI within 300 m instead of within 100 m did not change our estimates (Table S11). Stratifying by degree of urbanisation showed contrasted associations between residential surrounding greenness and mouldy area size (p -interaction < 0.0001). In rural areas, higher risk was observed for both area sizes ($< 0.2 \text{ m}^2$ and $\geq 0.2 \text{ m}^2$), with more marked associations for the larger size. In contrast, in Paris, residential surrounding greenness was associated with a lower risk of mouldy areas $< 0.2 \text{ m}^2$. Restricting the analyses to participants living outside Paris, residential surrounding greenness was positively associated with mouldy area size, and no statistically significant heterogeneity was observed according to dwelling type (Table S8).

4. Discussion

Among participants from a large French population-based cohort, we found associations of geographical and environmental contexts with visible mould and mouldy area size. The likelihood of mould contamination was lower in densely populated areas overall, except in Paris and its suburbs, as well as in the functional urban area of Paris, where the

risk was higher compared to rural municipalities or municipalities outside functional urban areas. Higher annual average temperature and precipitation were associated with an increased likelihood of mould contamination, while greater thermal amplitude was inversely associated. Living in flooded areas was also associated with a higher risk of mould contamination. Higher surrounding greenness was associated with an increased risk of mould contamination among participants living outside Paris. The associations were overall more marked for the largest mouldy areas.

Our study has both strengths and limitations. One of the strengths of our study is the spatial approach considering geographical and environmental characteristics related to indoor mould, which is rarely addressed in the literature. This allows us to shed new light on the spatial distribution of indoor mould and its associations with geographical and environmental contexts. Additionally, the use of mouldy area size in French dwellings at a large scale to assess contamination severity provides deeper insight into how these factors relate to the extent of mould contamination, going beyond the presence or absence of visible mould. We acknowledge that a lack of representativeness of the population cannot be excluded, since participants in the CONSTANCES cohort were randomly selected from beneficiaries of the National Health Insurance Fund (CNAM), which does not include agricultural and self-employed workers affiliated with other health insurance funds, and recruitment was conducted through only 24 participating Social Security health examination centres, leading to limited geographical representativeness of the French population at baseline. However, over time, participants have moved to different areas across France, thereby improving geographical coverage. In addition,

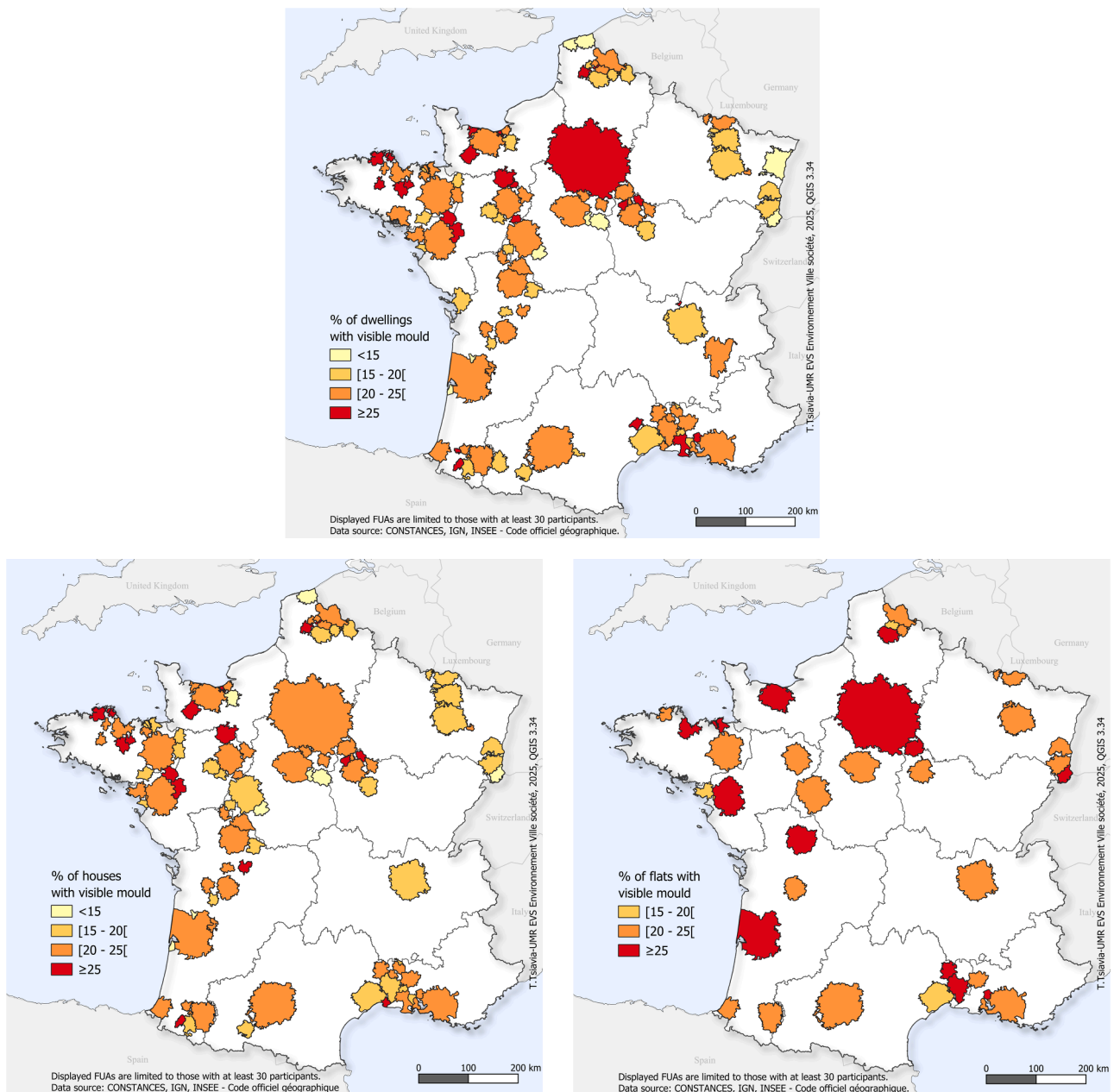


Fig. 3. Visible mould by urban functional area.

CNAM covers around 85 % of the French population. We cannot exclude some selection bias due to the lost to follow-up participants over time in CONSTANCES. We assessed mould contamination using a standardized, self-reported questionnaire designed by experts, with illustrations to make the participants' answers as standardised as possible. Furthermore, a toll-free number was provided in case they had question. We recognize that the accuracy of participants' identification of mould contamination cannot be guaranteed and consider underestimation of mould contamination is more likely than overestimation in our study. Whatever the definition used for mould contamination, the results were consistent, which emphasizes their robustness. If misclassification bias exists, it is likely non-differential as exposure assignments are based on objective geographical and environmental characteristics rather than participant reporting. Continuous climatic parameters were based on long-term monthly averages (1971–2000), which may not fully reflect environmental conditions at the time of the 2019 survey; however, observed associations were overall consistent with the literature [1,3].

To better capture the multi-dimensional nature of urban environments, we examined three distinct urbanisation indicators: urbanicity, size and type of functional urban area. We found significant associations between geographical contexts and visible mould, and reported for the first time associations with mouldy area size. Living in Paris and its suburbs was associated with a higher risk of visible mould. Similarly, the risk was higher for the functional urban area of Paris compared to rural areas or areas outside the functional urban area, particularly for larger mouldy area size. These findings, along with the attenuated association in more densely populated areas, suggest that overcrowding in dense urban centres, where the occupant-surface ratio was higher, may contribute to mould risk, potentially offsetting the advantages of better housing infrastructure. As expected, when considering the functional urban area type classification, the pattern differed: compared to municipalities outside functional urban areas, living in commuting area, secondary centre, or central municipality was associated with a lower risk of visible mould. This contrast may arise not only from differences in

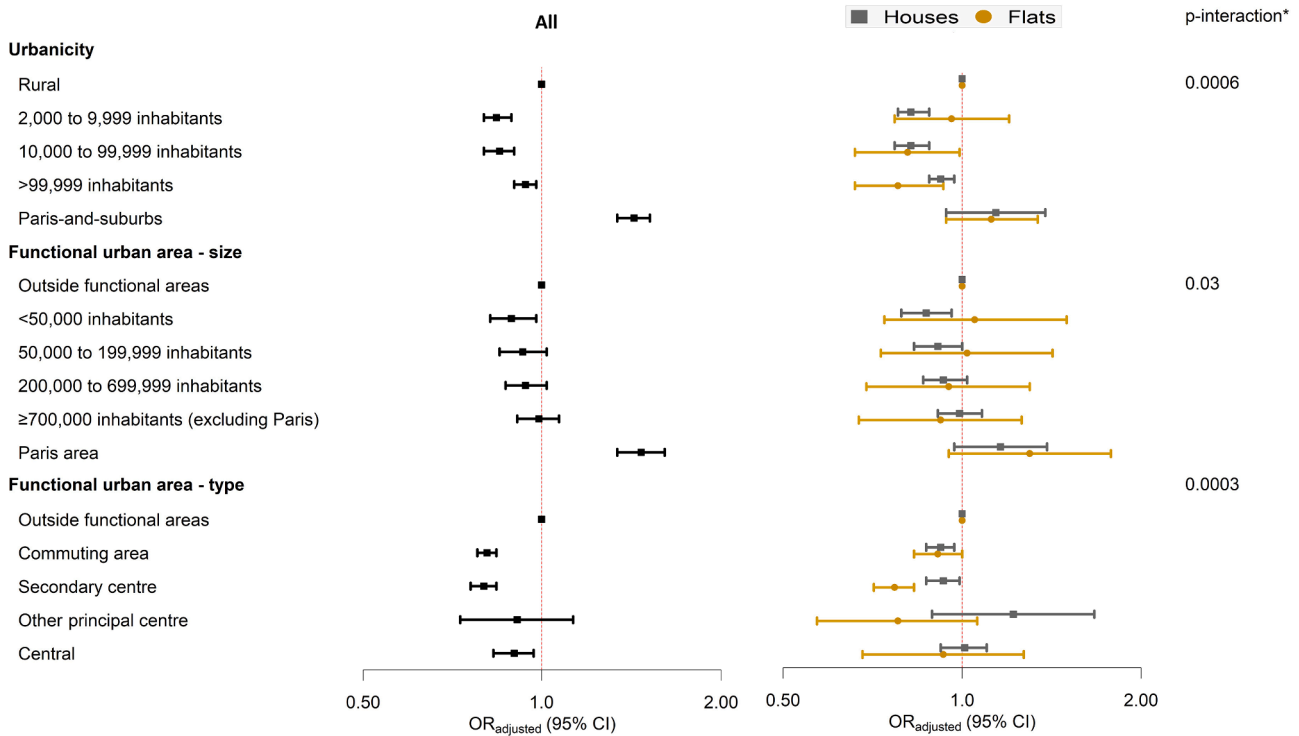


Fig. 4. Associations between geographical contexts and the presence of visible mould in all and according to dwelling type. Odds ratio (OR) and 95 % confidence intervals (95 % CI) estimated by logistic regression models adjusted for FDep. *: threshold p value =0.0019.

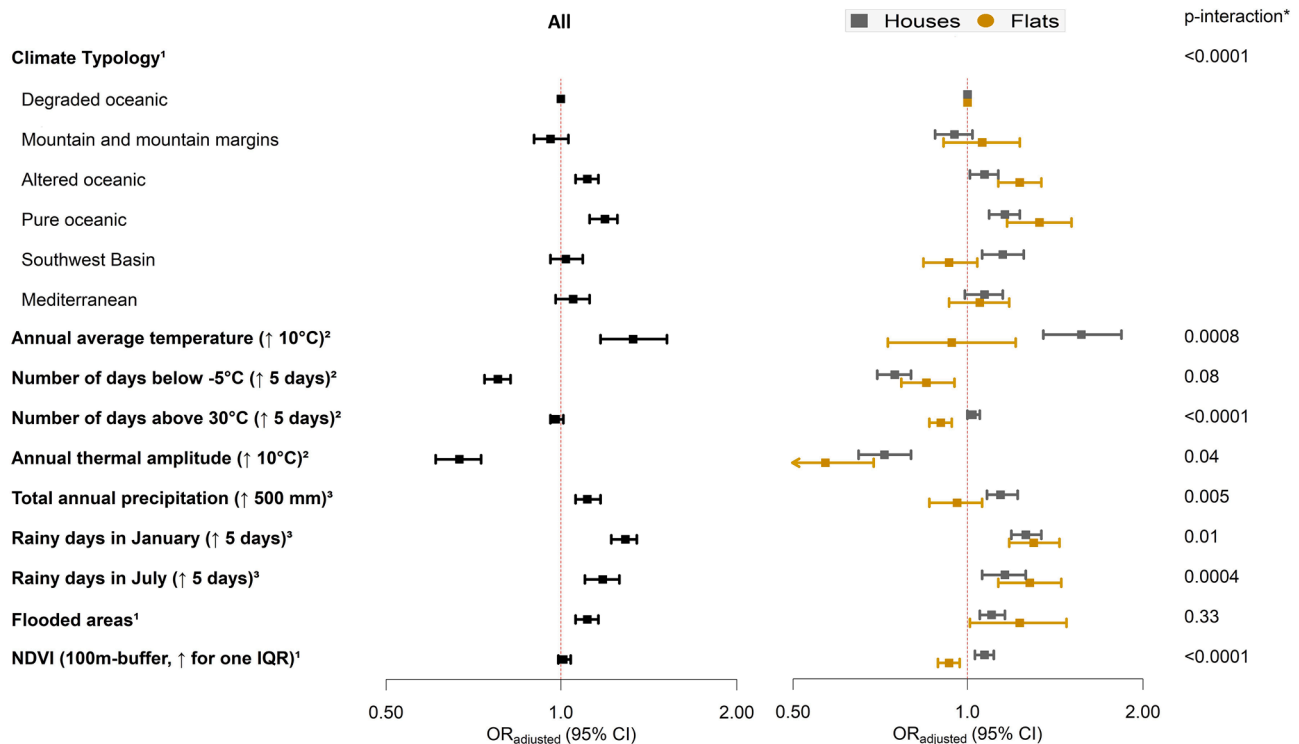


Fig. 5. Associations between environmental contexts and the presence of visible mould in all participants and according to dwelling type. Odds ratio (OR) and 95 % confidence intervals (95 % CI) estimated by logistic regression models: (1) adjusted for French deprivation index (FDep) and occupant-surface ratio; additionally adjusted for (2) total annual precipitation or (3) for annual average temperature based on directed acyclic graphs (Fig. S2). thermal amplitude: min-max temperature range. *: threshold p value =0.0019.

reference categories but also from the heterogeneity of area categories with respect to population size. For example, municipalities in the ‘Commuting area’ category may be part of either very large (like Paris)

or very small functional areas. Another explanation is the greater granularity of the functional urban area typology, which captures functional and socio-economic heterogeneities, including lifestyle

Table 2
Associations between geographical contexts and maximum of mouldy area size.

	All areas (n = 97,825)	
	<0.2 m ² n = 19,353 OR (95 % CI)	≥0.2 m ² n = 2621 OR (95 % CI)
Urbanicity		
Rural	ref.	ref.
2000 to 9999 inhabitants	0.84 (0.79–0.89)	0.90 (0.78–1.05)
10,000 to 99,999 inhabitants	0.85 (0.80–0.90)	0.85 (0.73–0.99)
>99,999 inhabitants	0.93 (0.89–0.98)	0.99 (0.88–1.11)
Paris and suburbs	1.38 (1.29–1.47)	1.80 (1.54–2.11)
Functional urban area - size		
Outside functional areas	ref.	ref.
< 50,000 inhabitants	0.92 (0.83–1.01)	0.76 (0.61–0.95)
50,000 to 199,999 inhabitants	0.97 (0.89–1.07)	0.69 (0.56–0.85)
200,000 to 699,999 inhabitants	0.98 (0.90–1.07)	0.74 (0.62–0.90)
≥700,000 inhabitants (excluding Paris)	1.02 (0.93–1.11)	0.84 (0.69–1.02)
Paris area	1.47 (1.34–1.62)	1.50 (1.21–1.86)
Functional urban area - type		
Outside functional areas	ref.	ref.
Commuting area	0.83 (0.80–0.86)	0.66 (0.60–0.73)
Secondary centre	0.82 (0.78–0.87)	0.65 (0.58–0.74)
Other principal centre	0.96 (0.77–1.21)	0.53 (0.26–1.06)
Central	0.88 (0.81–0.96)	0.97 (0.80–1.16)

Odds ratio (OR) and 95 % confidence intervals (95 % CI) estimated by non-ordinal polytomous logistic models adjusted for FDep. No mould (n = 75,851) was the reference category.

Table 3

Associations between environmental contexts and maximum of mouldy area size.

	All (n = 97,825)	
	<0.2 m ² n = 19,353 OR (95 % CI)	≥0.2 m ² n = 2621 OR (95 % CI)
Climate typology¹		
Degraded oceanic	ref.	ref.
Mountain and mountain margins	0.96 (0.90–1.03)	0.99 (0.82–1.19)
Altered oceanic	1.09 (1.04–1.14)	1.23 (1.10–1.38)
Pure oceanic	1.16 (1.10–1.23)	1.37 (1.19–1.58)
Southwest Basin	1.01 (0.94–1.08)	1.11 (0.94–1.32)
Mediterranean	1.01 (0.94–1.08)	1.36 (1.16–1.59)
Annual average temperature († 10 °C)²	1.21 (1.06–1.39)	2.72 (1.95–3.80)
Number of days below –5 °C († 5 days)²	0.80 (0.76–0.85)	0.60 (0.51–0.69)
Number of days above 30 °C († 5 days)²	0.97 (0.95–1.00)	1.06 (1.00–1.12)
Annual thermal amplitude († 10 °C)²	0.68 (0.61–0.74)	0.62 (0.49–0.78)
Total annual precipitation († 500 mm)³	1.11 (1.05–1.18)	1.11 (0.97–1.26)
Rainy days in January († 5 days)³	1.27 (1.21–1.34)	1.38 (1.22–1.57)
Rainy days in July († 5 days)³	1.18 (1.10–1.27)	1.18 (0.99–1.40)
Flooded areas⁴	1.11 (1.06–1.17)	1.07 (0.95–1.21)
NDVI (100m-buffer, † for one IQR)¹	1.02 (0.99–1.05)	0.94 (0.86–1.01)

Odds ratio (OR) and 95 % confidence intervals (95 % CI) estimated by non-ordinal polytomous logistic models: (1) adjusted for French deprivation index (FDep) and occupant-surface ratio; (2) additionally adjusted for total annual precipitation; (3) additionally adjusted for annual average temperature. Analyses on flooded areas were restricted to houses and ground-floor flats only. Thermal amplitude: min–max temperature range.

patterns such as commuting and urban living, that broad urbanicity categories may overlook [31]. Our results are in line with previous studies highlighting spatial disparities in mould exposure across France. Data from the French indoor environment quality observatory national campaign (2003–2005) showed that the frequency of dwellings with visible mould vs. no visible mould was higher in rural (46 % vs. 38 %) and peri-urban (44 % vs. 32 %) areas but not in urban zones (10 % vs. 30 %), suggesting a significant association between mould and residential setting ($p < 0.05$) [32]. Other studies have reported higher levels of mould contamination in dwellings located in agricultural settings, particularly on livestock farms, compared with rural non-farming homes

[33], and differences across urban, peri-urban, and rural housing [14, 34]. These disparities may reflect underlying economic, social, and ethnic inequalities that influence housing quality, maintenance, and exposure conditions. Consistent with previous study [35], our results also showed that participants living in an IRIS area where more than 50 % of the buildings were constructed up to 1970 reported more frequently visible mould than those living in areas where more than 50 % of the buildings were constructed from 1971 onwards. Overall, these findings highlight the importance of considering multiple contextual indicators to better characterize environmental disparities and housing conditions across territories. They support the need to account for both geographical and socio-structural contexts when designing strategies to prevent and reduce indoor mould contamination.

Living in altered and pure oceanic climate regions, compared to degraded oceanic zones, was associated with a higher risk of visible mould and more marked association for larger mouldy area size. This may reflect the lower thermal amplitude, higher humidity and more frequent precipitation typical of these regions [25], which are known to promote indoor mould growth [36]. The lower frequency of housing-related issues such as lack of ventilation and heating difficulties in these areas further supports the predominant role of climatic factors. The risk of visible mould increased with higher annual average temperatures, consistent with previous studies across different climate zones. A meta-analysis of buildings in 31 European countries found higher associations between temperate climates and mould prevalence, and between warm climates and combined indicators (dampness/mould), compared to cold climates [3]. Similarly, Norbäck et al. reported a positive association between annual average temperature, and both reported and observed dampness and mould in a study of 7127 dwellings across 22 European centres [1]. We found that total annual precipitation was positively associated with visible mould. This is consistent with an European study showing that a 100 mm increase in annual precipitation was associated with a 1.1-fold increase in the likelihood of visible indoor mould [1]. This risk was more marked for larger mouldy area size. Although building designs are often adapted to local rainfall levels, our findings highlight the need for further improvements in areas exposed to heavy precipitation and flooding. Living in flooded areas was associated with the presence of visible mould, particularly for mouldy area size smaller than 0.2 m², but not for larger ones. This may reflect that during an extreme event like a flood, sanitation measures are more likely to be taken before the contamination spreads, especially since these interventions are often covered by insurance in France. With climate change expected to bring higher average temperatures and more irregular rainfall patterns, strengthening buildings' resilience to moisture and flooding is increasingly essential [37, 38].

The initially observed divergent associations between residential surrounding greenness and visible mould in houses *versus* flats may partly reflect the specific characteristics of Paris. After excluding participants from Paris in sensitivity analysis, residential surrounding greenness was consistently and positively associated with visible mould and mouldy area size < 0.2 m², with no significant difference between houses and flats. These associations remained consistent when using either 100-metres or 300-metres buffer sizes, which is expected given the high correlation between these measures. These results showed that vegetation might influence the presence of mould both in the immediate vicinity of the dwelling and in its near surroundings. They suggest that the earlier heterogeneity was driven by the atypical urban environment of Paris, where NDVI levels are generally low, even near green spaces [30], and may reflect more artificial or managed vegetation. Our results remained unchanged when restricting the analyses to participants with exact IRIS-level geocoding, highlighting the robustness of the findings. Overall, these results indicate the importance of considering urban context when interpreting the impact of surrounding greenery on mould risk. Future analyses could consider mediation approaches to separate the direct and indirect effects of geographical and environmental

contexts, for example through ventilation practices such as window opening, or the use of dehumidification devices, if such data were available.

In conclusion, geographical and environmental contexts were associated with mould contamination. These factors should be considered in prevention strategies and in efforts to improve the management of mould contamination. Associations of temperature and annual precipitation with visible mould highlight the importance of adapting building design to local climatic conditions. With climate change leading to higher mean temperatures and more irregular rainfall patterns, the risk of dampness and mould contamination in buildings may rise, underscoring the growing necessity of climate-resilient construction in the future.

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Data access and availability

The data used in this study are not publicly available. Access can be granted upon approval of a research proposal by the Constances cohort international scientific committee and provided the project meets the legal requirements set by the French data protection authority (Commission nationale de l'informatique et des libertés, CNIL) under the General data protection regulation (GDPR). The use of cohort data is governed by the Constances cohort access charter. The data access procedure is available on the Constances cohort website (<https://www.constances.fr/en/scientific-area/access-to-constances-2/>).

CRedit authorship contribution statement

Tajidine Tsiavia: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Emilie Fréalle:** Writing – review & editing, Methodology, Conceptualization. **Marcel Goldberg:** Writing – review & editing, Resources. **Emeline Lequy:** Writing – review & editing, Resources. **Céline Ribet:** Writing – review & editing, Resources. **Marie Zins:** Writing – review & editing, Resources. **Laurent Orsi:** Writing – review & editing, Methodology, Conceptualization. **Rachel Nadif:** Writing – review & editing, Methodology, Conceptualization. **Christina Aschan-Leygonie:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.buildenv.2025.114163](https://doi.org/10.1016/j.buildenv.2025.114163).

Data availability

The data that has been used is confidential.

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