CS-N0W WPG11 Mapping Climate Related Hazards to Buildings

Final Report

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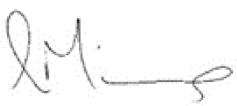
Sign off



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Key findings

This study presents the findings from an assessment of exposure and sensitivity of the UK building stock to climate-related hazards. The main output includes spatial mapping of projections of five climate-related hazards (extreme wind, wind-driven rain, subsidence, wildfires, and pests) under future climate and warming scenarios. These scenarios consisted of Representative Concentration Pathways (associated with the level of emissions in our atmosphere) and Global Warming Levels (associated with overall warming within the global climate system). The key findings of which are presented below:

- **Extreme wind:** Coastal areas throughout the UK are particularly exposed to high-wind gusts (referred to throughout this report as extreme wind). Buildings in the northwest of Scotland, particularly along the coast, historically have been particularly exposed to high extreme wind. Inland areas are historically less exposed, with London and surrounding areas further south, as well as parts of Wales, least exposed.[1] Home insurance claims for storm damage (including extreme wind and associated debris) totalled £133 million in 2023. Under future climate scenarios, these trends are expected to continue. By 2060-2080, exposure to extreme wind is projected to increase across all parts of the UK, in comparison to both the historical, and 2020-2040 periods, with the same spatial pattern of coastal areas and the Scottish Highlands being most exposed and inland areas in the south of England least exposed. Mobile homes and buildings with traditional roofing types and materials, especially those in exposed areas like coasts, rivers, or open land, may be increasingly exposed to extreme wind.
- **Wind-driven rain (WDR):** Across the UK, exposure to WDR is greatest for southerly, south-easterly, south-westerly, and westerly wind directions. Lower exposure is seen for northerly, north-easterly, easterly, and north-westerly wind directions. Buildings currently on the northwest coast of the UK have slightly higher exposure to south-easterly WDR, and the west of the UK is more exposed to southerly and westerly WDR, particularly the western coast of Scotland. These spatial trends are projected to remain similar but with increased exposure in all areas under a 2°C Global Warming Level (GWL), further increasing exposure under a 4°C GWL. As GWLs rise, slight

[1] Weather damage insurance claims worst on record | ABI

decreases in exposure are seen across four specific wind directions: northerly, north-easterly, easterly, and north-westerly. These are found in small areas across the Northeast of Scotland. Buildings made with relatively porous materials are potentially sensitive to greater volumes of WDR due to water absorption, especially for buildings with cavity wall construction.

- **Subsidence:** Susceptibility to subsidence due to clay shrink-swell is driven by the underlying mineralogical and lithological characteristics of the geology as well as climate. Much of the susceptible formations are in the south-east of England and the Midlands, and most of the North and North-West does not currently experience clay shrink-swell. By autumn of 2024, home insurance claims for subsidence had reached £66 Million, up by 61% from the same period in 2023[2]. Areas of susceptibility are projected to expand and by 2030, clay shrink-swell subsidence is projected to increase across London, Essex, Medway, and Cambridgeshire. By 2070, this spatial trend is projected to spread outwards, with the majority of southeastern England and parts of the east Midlands projected to experience an increase in susceptibility to clay shrink-swell. Climate change affects subsidence as clay-rich geological deposits are susceptible to volume change due to changes in water content from changing rainfall and temperature patterns, leading to shrinking and swelling. Buildings on clay-rich ground, especially lightweight structures with shallow foundations, are most sensitive to subsidence.
- **Wildfires:** From 1981 to 2010, the east Midlands, Norfolk, and counties just north of London have been most exposed to potential wildfire occurrences. Under a moderate climate scenario, Representative Concentration Pathway (RCP) 4.5, the same spatial pattern is projected to occur, but with a higher degree of exposure in a UK context, with the addition of central southern England. Under a high emissions scenario, RCP 8.5, relatively high exposure to wildfires is projected to occur across most of southern England excluding Greater London, the east Midlands, and further north in east Yorkshire. Buildings constructed using combustible materials (e.g. timber-framed), are particularly sensitive to wildfires, especially those that are in rural locations and near vegetation.

[2] Year-to-date property claims payouts hit £4.1 billion | ABI

- **Pests:**

  Under a 2°C GWL, most of the UK is projected to *not* experience temperatures within the optimal temperature range for pest development, and therefore projected to experience no exposure, with some optimal temperatures projected in the East of England, and therefore low exposure, for the following species:

  - *Hylotrupes bajulus* (house longthorn beetle);
  - *Xestobium rufovillosum* (death watch beetle);
  - and *Oligomerus ptilinoides* (bamboo powder post beetle). This species is not currently found in the UK, but conditions may support their survival in the future, should they have a route to introduction, and therefore could become established, although exposure to these conditions is projected to be low.

  Under a 4°C GWL:

  - Exposure to optimal temperatures for the potential development of the beetles listed above is projected to spread, with low exposure projected across the UK, but with slightly higher exposure to optimal temperatures projected in southeastern England.
  - The UK is projected to experience at least medium exposure temperature conditions that are optimal for the following species:
    - *Stegobium paniceum* (biscuit beetle), with suitable conditions for this species projected in the East Midlands and southern England, excluding north Devon.
    - *Coptotermes formosanus* (Formosan subterranean termite), with high exposure in Northern Ireland, western Scotland, coastal Wales, and most of southern England. This species is not currently found in the UK, but conditions may support their survival in the future, should they have a route to introduction, and therefore could become established.

  Buildings of timber framed construction and/ or timber roofs are particularly sensitive to pests.

About CS-N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5.5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation, and climate action, and improves accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing, and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research partners **Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

Contents

Acronyms

Acronym	Definition
BGS	British Geological Survey
CCC	Climate Change Committee
CS-N0W	Climate Services for a Net Zero Resilient World
DESNZ	Department for Energy Security and Net Zero
FWI	Fire weather index
GDD	Growing degree days
GIS	Geographical Information Systems
GWL	Global warming level
IPCC	Intergovernmental Panel on Climate Change
LSOA	Lower layer Super Output Area
OA	Output Area
RCP	Representative concentration pathway
REA	Rapid Evidence Assessment
SSBSS	Shrink Swell Building Susceptibility Score
UCL	University College London
UKCP18	United Kingdom Climate Projections 2018
WDR	Wind-driven rain
WUI	Wildland-urban interface

1. Executive summary

This report presents the key outputs from a study exploring exposure and sensitivity of the UK building stock to climate-related hazards. The purpose of this work is to enhance the Department for Energy Security and Net Zero's (DESNZ) evidence base on risks from climate-related hazards to the UK building stock. 2024 saw a record £5.7 Billion in property claims (up 28% from 2023) driven by damage to homes and businesses from significant and consistent bad weather[3]. Claims were associated with storms, heavy rain, and subsidence[4], reflecting a trend of increasingly severe climate-related hazards and associated damages to homes and buildings. This poses a significant challenge to the UK's economy, homeowners, and building stock as the trend is expected to continue throughout the century. This study is a first step in addressing the research gap to understand how the building stock will be affected in the future, and to what extent damages will continue.

A key output of the study consists of a Hazard Mapping Visualisation tool; an interactive map presenting the exposure of the UK building stock to extreme wind, wind-driven rain, subsidence, wildfires, and pests, in the recent past, to represent the present day baseline, and projected under different future climate scenarios. The tool is not currently available for public access. The tool is internal to DESNZ as it is incomplete, awaiting further development, specifically the integration of National Buildings Database to feed into future research. A supplementary qualitative analysis identified the sensitivity of building characteristics (type, fabric, design, and age) to these hazards to contextualise the mapped results (see Section A.1.2).

Figure 1 presents key results for each of the hazards, according to the most extreme climate scenario (Representative Concentration Pathway 8.5 or Global Warming Level 4°C), showing outcomes towards the end of the century (exact time period is dependent on the specific hazard and climate scenario). Key areas of exposure to the five climate-related hazards in the UK vary by region and hazard:

[3] More action needed to protect properties as adverse weather takes record toll on insurance claims in 2024 | ABI
[4] Year-to-date property claims payouts hit £4.1 billion | ABI

- **Extreme wind:** Extreme wind is most severe in the northwest of Scotland, particularly in the Highlands and coastal areas, while the southeast of England is least exposed.
- **Wind-driven rain:** Wind-driven rain predominantly affects the western UK, with the highest exposure along the western Scottish coast.
- **Subsidence:** Subsidence is concentrated in London, Essex, Medway, and Cambridgeshire, projected to expand across southeastern England and the east Midlands by 2070.
- **Wildfire:** Wildfire exposure is highest in the east Midlands and parts of East Anglia, with future projections of wildfire exposure including the same regions as well as spreading to parts of Gloucestershire, Oxfordshire, and Hampshire.
- **Pests:** Exposure to pests differs by species. Both the *Oligomerus ptilinoides* (bamboo powder post beetle) and the *Coptotermes formosanus* (Formosan subterranean termites) have not been observed in the UK previously, but the air temperature conditions that may support the development of these pests are projected to occur , while all other assessed species have been observed in the UK. Temperatures that support the development of the *Hylotrupes bajulus* (house longhorn beetle), *Xestobium rufovillosum* (deathwatch beetle) and *Oligomerus ptilinoides* (bamboo powder post beetle), are projected in southeastern England under higher global warming scenarios, while the southern and western coastal regions are projected to be exposed to optimal temperatures for *Coptotermes formosanus* (Formosan subterranean termites). Exposure to suitable temperature conditions for the *Attagenus smirnovi* (brown carpet beetle) is projected in southeastern England and a corridor between Cardiff, Birmingham, and Leeds. Optimal temperature conditions for the development of the *Anobium punctatum* (common furniture beetle) are projected to occur in areas south of Yorkshire, and for the *Stegobium paniceum* (biscuit beetle) in the East Midlands and southern England under a higher warming scenario.

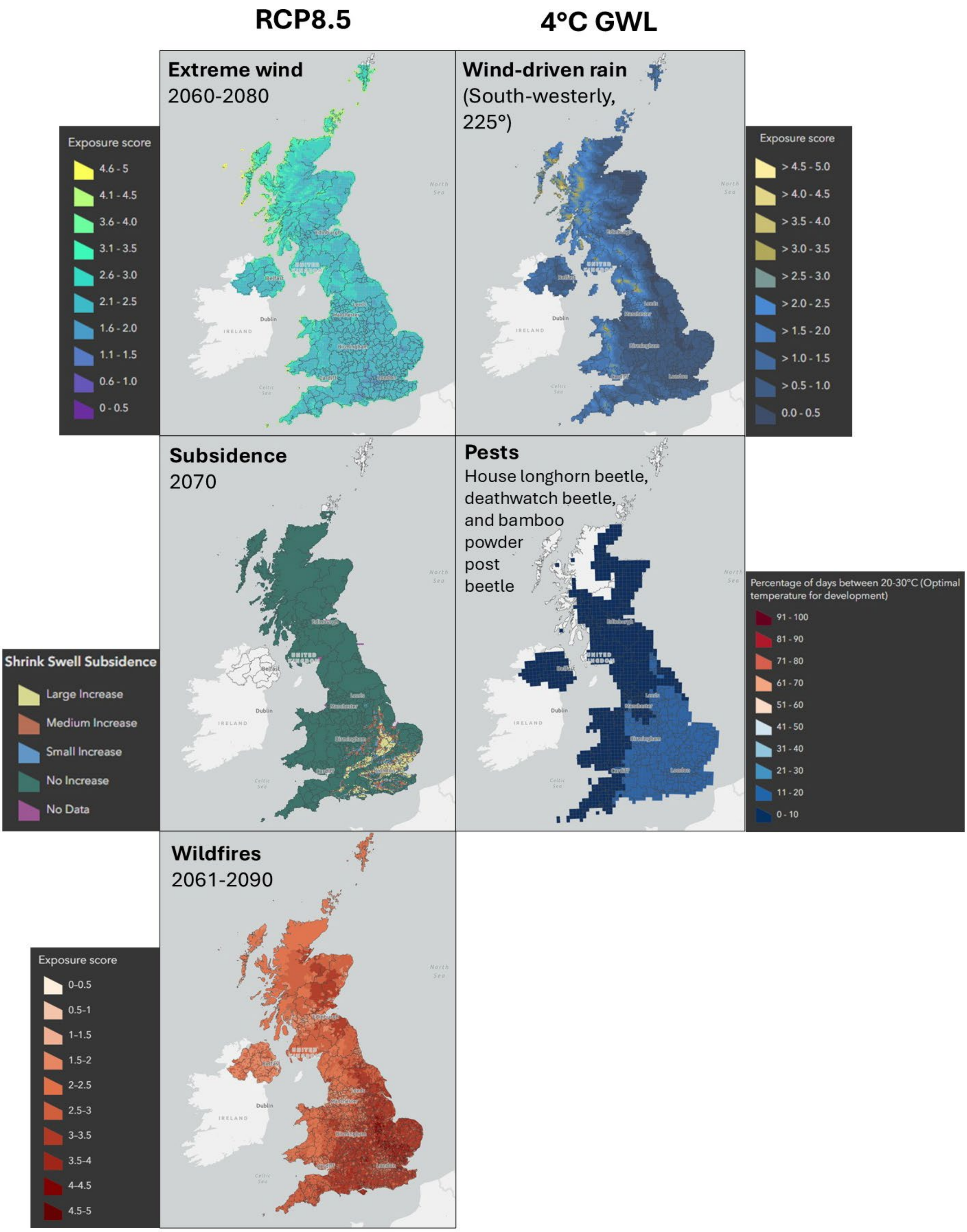
The Hazard Mapping Visualisation tool, underlying data, and results can be used to understand relative exposure of the building stock to the five climate-related hazards across the UK. The outputs are spatially relevant to *at least* a 12km grid, hence are also suitable for identifying the level of exposure for specific areas or local authorities of interest. This can contribute to more comprehensive analysis of the full climate risk chain by combining the findings with a more comprehensive assessment of vulnerability (combining assessments of sensitivity and adaptive capacity), to determine potential impact and ultimately level of risk.

This research can underpin further efforts to further improve the evidence base for enhancing adaptation to climate-related hazards in the UK's built environment. Suggestions for further research include adding and improving data inputs to the interactive map, such as:

- Integrating data from the National Buildings Database (NBD) into the tool to identify risk from exposure in context of the sensitivity of buildings in a given area.
- Expanding the input information for the pest analysis beyond air temperature
- Upgrading to the use of the premium dataset for the subsidence analysis
- Using a wider range of climate models throughout the analysis to account for uncertainty
- Integrating analysis of additional climate-related hazards that may affect buildings, such as potential corrosion from carbonation in reinforced concrete buildings

More in-depth analysis is required to build the initial analysis of sensitivity into a full assessment that can contribute to an understanding of climate-related impacts and risks of these hazards on buildings in the UK.

Figure 1 Exposure to all climate-related hazards according to the highest climate scenario and more distant future period



2. Introduction

The UK Government recognises the potentially damaging impact of climate change on the UK's housing and built environment. The Department for Energy Security and Net Zero (DESNZ) are building an evidence base to understand the potential risk that climate-related hazards pose to the UK building stock and the ability to plan and build new housing. A technical evidence gap was identified in the UK's third Climate Risk Assessment (CCRA3) (regarding risk H5), with a lack of evidence and understanding as to how key climate-related hazards affect buildings across the UK and how these will develop into the future. As a result, developing policy for the design, construction, and retrofit of buildings in a manner, that considers risk posed by hazards and potential adaptation options, is a challenge. To contribute to the evidence base, this study **spatially mapped physical exposure of the UK building stock to five climate-related hazards under potential future climate and warming scenarios.** A supplementary Rapid Evidence Assessment was also conducted to **identify and categorise existing evidence relating to the sensitivity of building characteristics** to climate-related hazards. "Exposure" and "sensitivity" are defined below:

Term	Definition *(as defined by IPCC Sixth Assessment Report)*
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; **infrastructure**; or economic, social, or cultural **assets** in places and settings that could be adversely affected.
Sensitivity	The **degree to which a system or species is affected**, either adversely or beneficially, by **climate variability or change**. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

The five climate-related hazards analysed include extreme wind, wind-driven rain (WDR), subsidence, wildfires, and pests. These were selected through consultation and agreement with DESNZ, to address priority research gaps, and feed into planned research activities. A key output of the study is a Hazard Mapping Visualisation tool. The tool is not currently available for public access; further development is planned to integrate improved datasets including on the building stock and to feed into future research.

This report presents the key findings, methodologies, and results gained from the study. The report is structured as follows. **Section 3** sets out the overall approach and scope, defining the climate-related hazards and building data considered in the analysis. **Section 4** presents the key findings from the assessment of exposure and sensitivity. Specifically, **Section 4.1** presents key findings from the development of the Hazard Mapping Visualisation tool, including underlying climate/building data, mapped outputs, and associated uncertainties. **Section 4.2** summarises the high-level findings from the review of evidence on sensitivity of buildings. **Section 5** summarises evidence gaps and next steps, including recommendations for use of the Hazard Mapping Visualisation tool, recommendations for improvement of the Hazard Mapping Visualisation tool, and further research required. The detailed methodology and findings are provided in the Appendices.

Throughout the report, key references have been included in the form of reference codes: for example, [F001]. See Reference for the full list of sources.

3. Approach and scope

The main activity under this study was the development of the Hazard Mapping Visualisation tool. The tool was designed to centralise and spatially map climate-related hazard data (including historical observations and projections, where available), to create a foundation for further analysis of climate risk to buildings. In future developments, this climate-related hazard data will be mapped against buildings data (the NBD). The tool was supplemented by a secondary Rapid Evidence Assessment[5] (REA) to identify and categorise existing evidence of building sensitivity to the five climate-related hazards.

[5] The REA involved carrying out literature searches, identifying relevant literature and extracting evidence pertaining to the sensitivity of building characteristics (type, fabric, design, and age) to the identified climate-related hazards.

3.1 Scope

3.1.1 Climate-related hazards

Five climate-related hazards were identified and agreed in consultation with DESNZ as drivers for climate-related impacts to the built environment. These include:

1. Extreme wind
2. Wind-driven rain
3. Subsidence
4. Wildfires
5. Pests

This is not an exhaustive list of climate-related hazards that may affect buildings. The scope was defined by DESNZ, to address priority research gaps associated with actions assigned to DESNZ under the 3rd National Adaptation Programme.

3.1.2 Spatial coverage

The geographic boundary of this study is UK wide. Spatial mapping is used to illustrate climate-related hazard data across the UK to demonstrate relative levels of exposure under a range of climate scenarios. LSOA (Lower Layer Super Output Area) level data is used to provide spatial building attributes for the analysis of **subsidence *only***. The LSOA level is a geographic area used in England and Wales for reporting small area statistics.

Planned updates to the Hazard Mapping Visualisation tool include the integration of the NBD, which is currently under development, to provide spatial building data attributes for all hazards.

3.1.3 Building characteristics

To understand how buildings are sensitive to climate-related hazards and potential drivers of this sensitivity, the Rapid Evidence Assessment (REA) was framed through a review of building 'characteristics' and their relationship to the climate-related hazards. Building characteristics included:

- Building type
- Building fabric
- Building design
- Building age

These characteristics were selected to align with planned research activities within DESNZ, which consists of a 'deep dive' on vulnerability of building types and fabrics across the UK. Further information on how these characteristics were considered can be found in Appendix 1.

3.2 Approach

The study was conducted in two phases: (1) Assessment of exposure and development of Hazard Mapping Visualisation tool, and (2) Rapid Evidence Assessment of literature to identify and categorise evidence of building sensitivity to climate-related hazards. This was delivered through the following tasks:

1. **REA of building sensitivity:** Conduct a rapid evidence assessment of literature to identify evidence of the sensitivity of different building characteristics to climate-related hazards. See Appendix 1 for full details of methodology and results.
2. **Climate data:** Identification of relevant climate-related hazard data from UKCP18 outputs. For each hazard, appropriate datasets were identified and collected, including key attributes of the data such as climate scenarios, timeframes, spatial resolution, percentiles etc. See Appendix 2 for full details of methodology and details of the datasets that were collected and used in the analysis.
3. **Analysis of exposure:** Calculation of relative exposure values based on analysis of the nature and range of available climate data (and, where possible, building data). See Appendix 3 for full details of methodology.
4. **Spatial mapping:** Generation of interactive maps that show exposure scores for all five climate-related hazards across the UK, allowing for comparison between recent past and projected future conditions and across UK regions. See Appendix 4 for full details of methodology.

5. **REA of potential adaptation options:** Conduct a rapid evidence assessment of literature to identify evidence of existing adaptation options that could be considered to reduce sensitivity or exposure of buildings to the five climate-related hazards. See Appendix 5 for full details of methodology and results.

During the collection of climate data and analysis of exposure, there was a focus for on simplicity to ensure the data and metrics used could clearly represent exposure levels. There was also a focus on alignments across hazards, where possible, in terms of the use of climate scenarios, timeframes and other data attributes. This was not always possible due to data availability, and each hazard was treated independently to ensure the analysis and results for each hazard is robust and useful, which was prioritised over consistency.

4. Key findings

The key outcomes of this study are presented below. This includes a summary of the results including extracts from the Hazard Mapping Visualisation tool and high-level insights on sensitivity of buildings and components of buildings. Full details of the methodology are included in the appendix.

4.1 Exposure to climate-related hazards

This section presents an overview of the key areas of exposure in the UK to the five climate-related hazards: extreme wind, WDR, subsidence, wildfires, and pests, outlining recent and projected trends of exposure based on climate model data. The findings are organised by climate-related hazard, introducing the hazard and the data used, and providing a summary of the key trends illustrated with examples of maps from the interactive tool.

The results are based on existing climate modelling and climate-related hazard data which contain considerable uncertainties[6]. The uncertainties, limitations of the analysis and associated assumptions have been presented alongside key findings.

[6] There is significant uncertainty associated with the use of climate projections data that underpins these maps. First, there is significant uncertainty surrounding the future climate scenario and/or global warming level the world will reach, which is dependent on the success of global mitigation efforts as well as complex feedback loops and tipping points that are difficult to model. There is significant disagreement between different climate models, as each model makes different assumptions that result in varying outputs that project different potential futures with regards to the magnitude of extreme

Details of the methodology behind developing the mapped results for each hazard can be found in Appendix 3 .

4.1.1 Extreme wind

Introduction to hazard

Extreme wind is a hazard that may pose a threat to buildings in the UK, due to potential damage from wind borne debris, pressure from high wind loads, uplift of building materials such as roofs, and erosion. Exposure to extreme wind has been assessed by mapping the hazard data only, which is the UK Climate Projections 18 (UKCP18) wind speed gust maximum data, detailed in Table 1. This data represents the maximum speed of a gust of wind, to occur in a year, measured in metres per second, at a 5km² resolution, according to a high emissions scenario (RCP8.5).

Table 1 Extreme wind data details

Dataset name	Unit of measurement	Data file format	Spatial factors		Timeframes			Climate scenarios	Percentiles
			Resolution	Coverage	Interval	Historical data	Projections		
Wind speed gust maximum	Metres per second	NetCDF	2.2km aggregated to 5km grid	UK wide	Annual	1981-2000	2021-2040 2061-2080	RCP8.5	n/a

The data for this hazard was sourced from the Centre for Environmental Data Analysis (CEDA) Archive.

Exposure scores have been assigned to this data, to express exposure to extreme wind on a scale of 0-5, with increasing value corresponding with higher wind gust speeds and therefore greater exposure to extreme wind.

heat events. There is also significant uncertainty associated with downscaling global climate models to the local level. The data presented here on a 2km², 5km², or 12km² grid is relatively high resolution, which risks indicating a false sense of certainty within the findings for each gridded area. Given the uncertainty associated with downscaled climate models, the findings should be considered indicative only. More detailed information on the uncertainty associated with the assessment of exposure can be found in this section (3) for each individual hazard.

The exposure scores are based on the percentile at which the wind gust speed falls within the distribution of wind gust speed values for all grid cells across the UK by 2080. Percentile values are scaled from the range 0-100 to the range 0-5. Further details of this methodology are outlined in Section A.3.1.

Summary of trends

Figure 2 Exposure to extreme wind

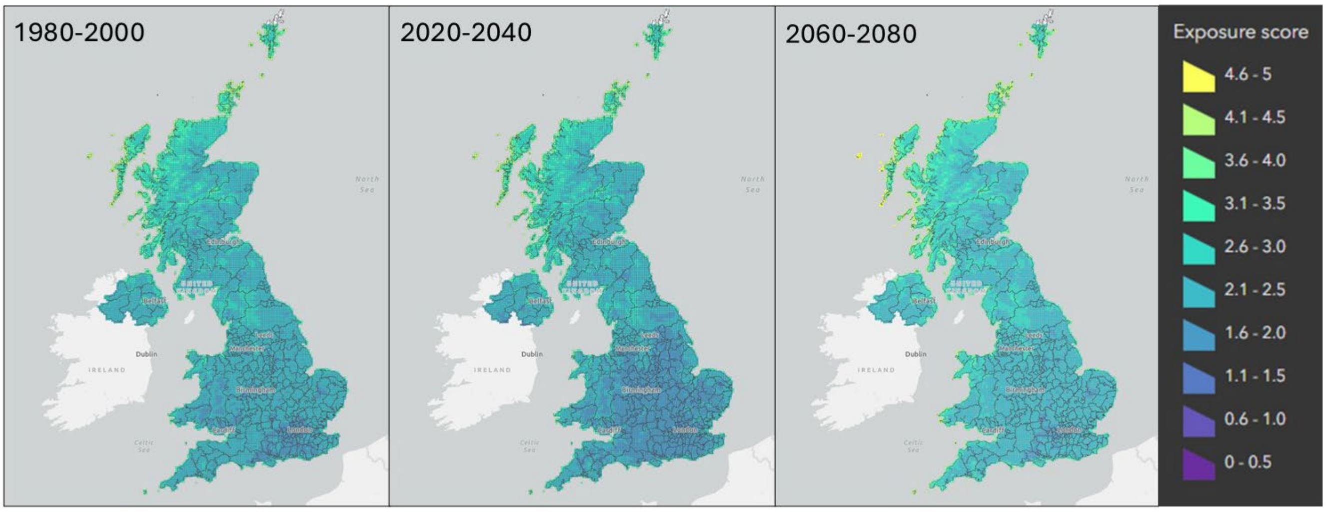


Figure 2 shows the spatial patterns of exposure to extreme wind across the UK, in the past (1980-2000), the near future (2020-2040), and the more distant future (2060-2080). Historically, extreme wind is more severe in the northwest of Scotland in the Highlands and particularly along the coast. Throughout the UK, coastal areas are particularly exposed to high wind gust speeds, and buildings along the coast are exposed to extreme wind (and associated wind-borne debris) due to a lack of wind-protection from surrounding buildings, making them more exposed to extreme wind than urban buildings. The inland area least exposed to extreme wind is the southeast of England. In 2020-2040, coastal areas and the Scottish Highlands are projected to be similarly exposed, but inland areas across England, apart from the northwest, are projected to become less exposed to high wind gust speeds. By 2060-2080, exposure to high wind gust speeds, referred to throughout this report as extreme wind, is projected to increase across all parts of the UK, in comparison to both the historical, and 2020-2040 periods, with the same spatial pattern of coastal areas and the Scottish Highlands being most exposed.

Uncertainties, limitations and assumptions

The limitations associated with the analysis of extreme wind include:

1. The wind gust data is projected at an elevation of 10m, which is a limitation as this may be higher than many buildings across the UK, and therefore the use of this data may not be completely indicative of the exposure of buildings to extreme wind. A calculation can be applied to this dataset to convert it to an elevation of 2m, but this was out of scope during this project due to timing and budget constraints.
2. The hazard data used here is split into 5 classes using the full range of available projection data. Therefore, the exposure classes were developed without consideration of a minimum wind gust speed that buildings are sensitive to, which may limit the usefulness of the exposure classes presented on the map when aiming to explicitly indicate *extreme* wind. Experts were consulted on current evidence regarding the minimum threshold of wind gust speed that buildings are sensitive to. No definitive answer was available, and further research is required to define this threshold, hence has not been included in the assessment.
3. The National Annex to BS EN 1991-1-4:2005+A1:2010, Eurocode 1 Part 1-4: "Wind actions on structures" states the need to include key factors such as altitude, terrain, and orography to calculate wind load on structures. A key limitation here is that it is uncertain whether the wind gust speed data considers these key factors – experts were consulted with no definitive conclusion, hence, it is unknown if this methodology comprehensively presents exposure of buildings to extreme wind.

4.1.2 Wind-driven rain

Introduction to hazard

Wind-driven rain is a hazard that may pose a threat to buildings in the UK as a result of potential water ingress and erosion of building materials. Exposure to WDR has been assessed by mapping the hazard data only, which is the UKCP18 annual index of WDR, outlined in Table 2, and represents the sum of all wind-driven rain spells in a year measured in volume of water. The data is at a 5km² resolution, according to two global warming levels (GWLs). This dataset was produced for a previous DESNZ funded research project.

Table 2 Wind-driven rain data details

Dataset name	Unit of measurement	Data file format	Spatial factors		Timeframes			Climate scenarios	Percentiles
			Resolution	Coverage	Interval	Historical data	Projections		
Annual index of wind driven rain	Annual index of wind driven rain (sum of all wind-driven rain spells in each year)	GeoJSON	2.2km aggregated to 5km grid	UK wide	Annual	1981-2000	Use of global warming levels (GWLs)	2°C and 4°C GWLs	Median of ensemble

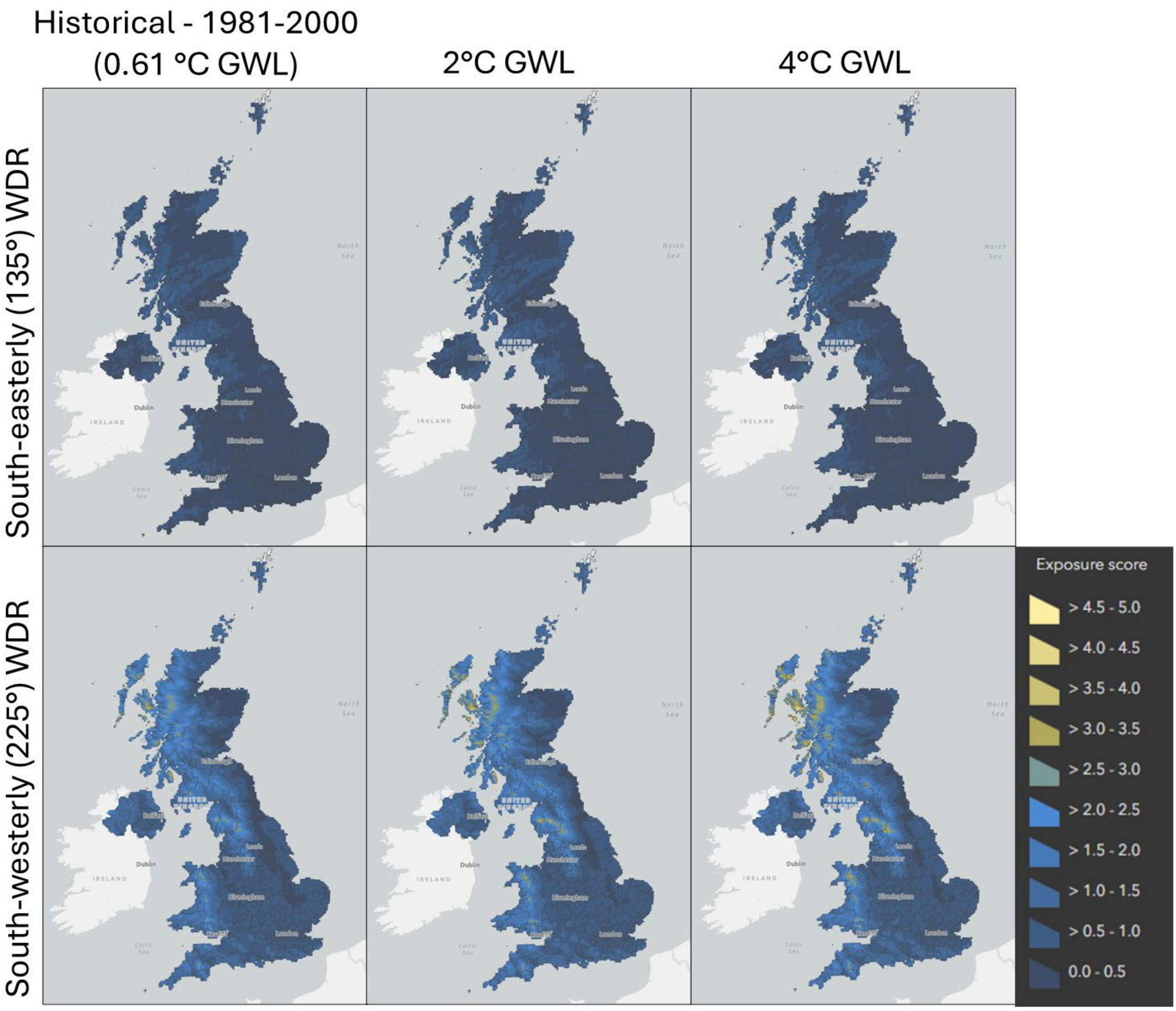
The data for this hazard was sourced from the Met Office Climate Data Portal.

The wind driven rain (WDR) exposure scores are assigned to this data on a scale of 0-5, with increasing value corresponding with a higher volume of rain blown from a given direction and therefore greater exposure to spells of WDR. The exposure scores are assigned per wind direction to provide exposure information for different wall orientations.

The exposure score is based on the percentile at which the volume of WDR sits within the distribution of WDR values for all grid cells across the UK at the higher GWL of 4°C. Percentile values are scaled from the range 0-100 to the range 0-5 to provide scores on a scale that align with exposure scores of the other hazards. Further details of this methodology are outlined in Section A.3.2.

Summary of trends

Figure 3 Exposure to south-easterly and south-westerly wind-driven rain



In the past (1981-2000) there has been relatively low exposure to WDR across most of the UK, with some areas more highly exposed. Noticeable patterns include: a slightly higher exposure to south-easterly WDR along the northwestern coast of the UK compared to the rest of the UK; the west of the UK is more highly exposed to southerly and westerly WDR especially the western Scottish coast; and there is an even greater exposure in the west of the UK to south-westerly WDR compared to all other wind directions. These spatial trends are projected to remain similar but with enhanced exposure in all areas under the 2°C GWL, and even further under the 4°C GWL. However, small decreases in exposure to WDR are seen in Northeast of Scotland, across four wind directions: northerly, north-easterly, easterly, and north-westerly. This pattern is projected to continue under 2°C and 4°C of global warming.

Uncertainties, limitations and assumptions

The limitations associated with the analysis of WDR include:

1. The hazard data used here is split into 5 classes using the full range of available projection data, meaning the exposure classes were developed without consideration of a minimum WDR that buildings are sensitive to. This assumes that any volume of WDR is useful to assess exposure to. This was agreed with WDR experts and aligns with the approach taken for extreme wind.
2. A key limitation to this analysis was a lack of alignment with an existing method for assessing exposure to WDR. Building regulation guidance Approved Document C: Site preparation and resistance to contaminates and moisture, contains a map that shows exposure to WDR. However, the method used to develop the map in the guidance is not clearly documented so on advice from a WDR expert at University College London (UCL), a different method, that aligns to international standards, was taken for this project.[7]

4.1.3 Subsidence

Introduction to hazard

Clay shrink-swell subsidence, from here on referred to as subsidence, is a hazard that may pose a threat to buildings in the UK, due to potential damage from the movement of clay soils beneath buildings. Across the country, clay-rich geological deposits, such as the London Clay Formation, are susceptible to volume change due to changes in water content.

[7] The key reasons for the difficulty to replicate the Building Regulations guidance map are: a) The lack of an upper bound, as the fourth, “very severe” class is defined by 100 litres per metre squared “or more”, and so it is difficult to determine how the classes were split up; and b) The WDR data used in the document is per spell whereas the data used for this project is per year.

The susceptibility to this shrinking and swelling varies, dependent on the clay mineralogy and lithology. Changes in annual rainfall and temperature patterns are increasing the chance of this volume change occurring [T102]. These changes can lead to ground movement that damages houses, near surface infrastructure, and other light structures.

Exposure to subsidence has been assessed using GeoClimate OPEN data, detailed in Table 3. This data was sourced from previous work conducted by the British Geological Survey (BGS) and provides exposure information on the potential for clay shrink-swell to occur, based on a combination of geological, hydrological and climate projection data. It is at a 2km² resolution, according to a high emissions scenario (RCP8.5).

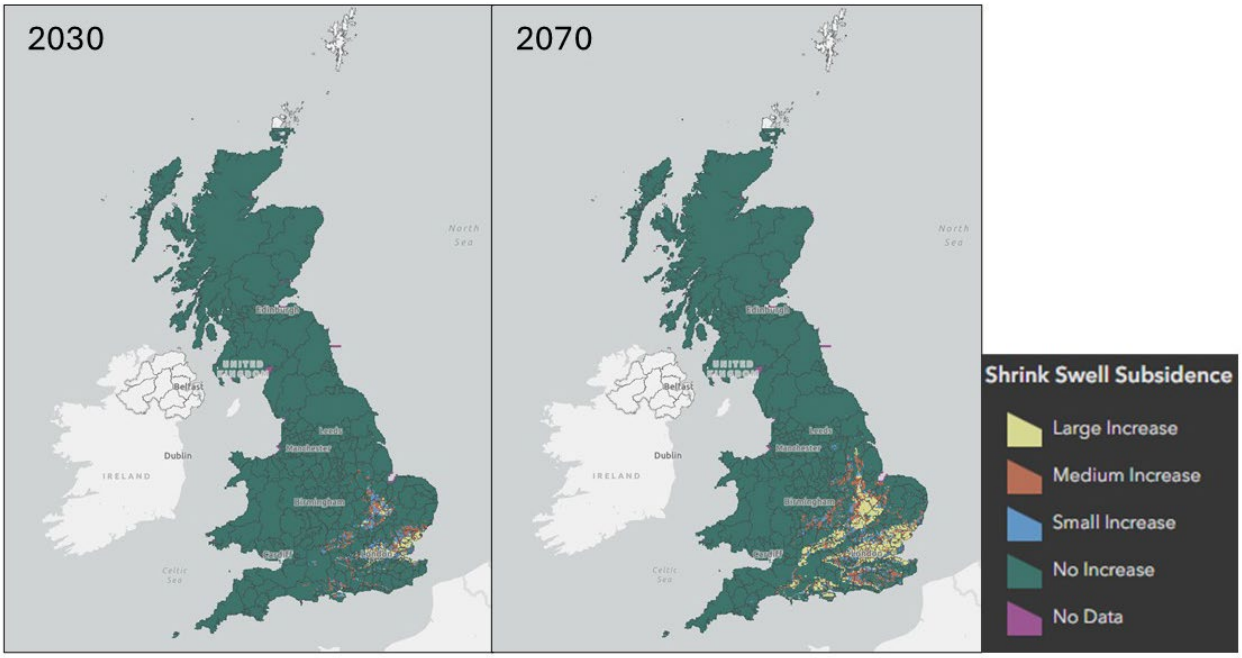
Table 3 Subsidence data details

Dataset name	Unit of measurement	Data file format	Spatial factors		Timeframes			Climate scenarios	Percentiles
			Resolution	Coverage	Interval	Historical data	Projections		
GeoClimate	Hazard rating (3 classes: 1. Improbable 2. Possible 3. Probable)	GIS polygon data (ESRI)	2km grid	UK wide	11-year intervals	None (only available with license)	2025-2035 2065-2075	RCP8.5	n/a

The subsidence maps differ from the other hazards as they provide an indication of sensitivity as well as exposure. The sensitivity information is also based on previous work conducted by BGS. The sensitivity scores are calculated by combining two subsidiary scores; the **GeoClimate OPEN score**, which provides an indication of hazard exposure, and the **SSBSS (Shrink Swell Building Susceptibility Score)** score, which provides an indication of hazard sensitivity, to provide an indication of no, small, medium, or large increase in sensitivity to subsidence. The **SSBSS** score is calculated based on BGS expert knowledge and experience, which reflects the controlling factors that influence the sensitivity of a building to clay shrink-swell subsidence. Lower Layer Super Output Area (LSOA) level data is used to represent building attributes including building type, age and number of storeys, and the LSOA polygons, with associated SSBSS values, were intersected with the GeoClimate OPEN scores to produce final sensitivity scores. More details on these inputs and the methodology of scoring subsidence sensitivity are in Section A.3.3.

Summary of trends

Figure 4 Projected exposure to clay shrink-swell subsidence



By 2030, the most noticeable changes to clay shrink-swell across the UK are projected to occur in London, Essex, Medway, and Cambridgeshire, with smaller increases projected to occur in Oxfordshire and Hampshire (Figure 4). By 2070, this spatial trend is projected to spread outwards from these locations and become more severe, with the majority of southeastern England and parts of the east Midlands projected to experience an increase in clay shrink-swell.

Uncertainties, limitations and assumptions

The limitations associated with the analysis of subsidence include:

1. GeoClimate OPEN is freely available generalised data and is intended for use in area and regional overview assessment, not for individual property analysis. The methodology, which takes worst-case clay shrink-swell susceptibility values, from within the 2km² grid, provides the user with a screening tool, with the ability to identify all potentially sensitive areas. It should be used as an indication as to where further detailed analysis or site investigation is required.

2. The use of LSOA level buildings data means that some of the building information is misclassified. All buildings within a LSOA polygon are assigned the majority value for that polygon. For example, the data on a LSOA polygon may show that there are 12 houses built between 1920 and 1930 and 18 built between 1940 and 1950 but it does not indicate which house has which age. It has therefore been necessary to determine the majority value for the polygon and assign this to all buildings within the polygon. In the above case, all 30 buildings would be classified as built between 1940 and 1950. This means that some buildings within the polygon are misclassified, which is a result of the resolution of the data used.
3. Due to a lack of spatial coverage in the LSOA level data, Northern Ireland is not included in the analysis of subsidence, leaving an evidence gap for this region. LSOA level data provides information on the building attributes across the spatial coverage. Without data regarding building attributes, the existing shrink-swell building susceptibility score could not be calculated.
4. GeoClimate clay shrink-swell is available in two versions: GeoClimate Open which has been used in this project and is a freely available overview dataset and GeoClimate Premium which is a licensed (paid-for) higher resolution and more detailed dataset. GeoClimate Open is designed as an overview for national use and GeoClimate Premium data is designed to provide increased detail to inform regional – local risk and mitigation assessments.
5. The Shrink Swell Building Susceptibility Scores (SSBSS) are fixed at modern values for future time periods and are not time-evolving. The static SSBSS scoring is consistent with the assessment undertaken for future exposure to wildfires, where the urban/rural and land cover scores are fixed at modern values.

4.1.4 Wildfire

Introduction to hazard

Wildfires may pose a threat to buildings in the UK, particularly to buildings located within close proximity to flammable, vegetated landscapes, where wildfires may spread from. Exposure to wildfires has been assessed using the Met Office Fire Danger data, detailed in

Table 4. This data represents the number of days per year that experience 'very high' fire danger, at a 12km² resolution, according to medium and high emissions scenario (RCP4.5 and 8.5, respectively). The 'very high' fire danger threshold for the UK is calculated by the Met Office.

Table 4 Wildfire data details

Dataset name	Unit of measurement	Data file format	Spatial factors		Timeframes			Climate scenarios	Percentiles
			Resolution	Coverage	Interval	Historical data	Projections		
Met Office Fire Danger	Number of days per year	GeoJSON	12km grid	UK wide	30-year intervals	1981-2010	2021-2050 2061-2090	RCP4.5 RCP8.5	Median of all members

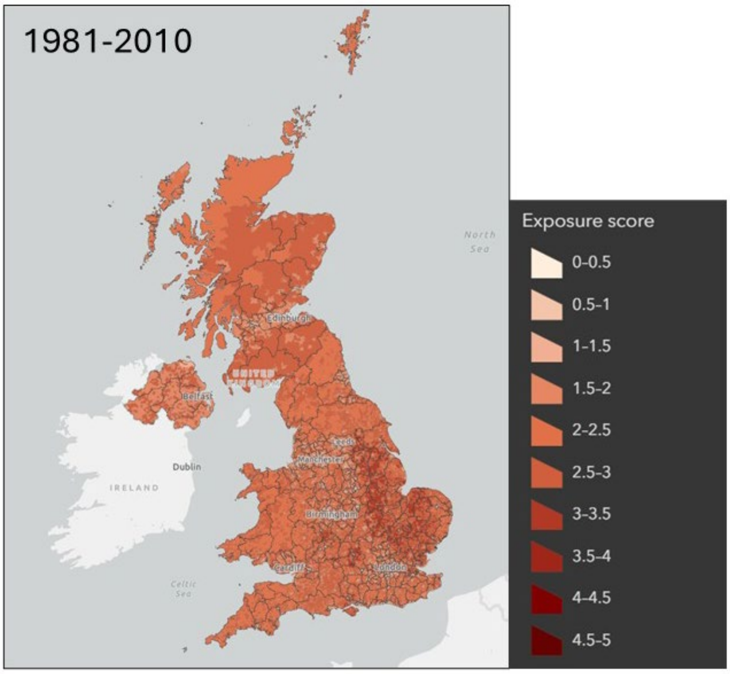
The data for this hazard was sourced from UK Climate Risk Indicators.

The wildfire exposure score is calculated by combining three subsidiary scores: the **fire danger score**; the **rural/urban score**; and the **land cover score**. The score for each component of overall exposure is expressed on a scale of 0-5, with increasing value corresponding to greater exposure to wildfire. The **fire danger score** is based on the annual number of days projected to experience very high fire danger under future climate change, using the hazard data described above. The fire danger score utilises the percentile at which each output area's projected number of fire danger days falls within the distribution of values for all output areas by 2090. Percentile values are scaled from the range 0-100 to the range 0-5. The **rural/urban score** is determined qualitatively based on expert judgement[8] on the extent of the rural/urban fringe in different rural/urban land categories and reflects the degree of connectivity between built-up areas to flammable (vegetated) landscapes. The **land cover score** is also determined qualitatively based on expert judgement, taking into consideration the propensity for extreme fire behaviour to occur on different land covers, given the fuel loads, fuel density and fuel structure. Section A.3.4 provides details of the individual scores and how they were combined.

[8] Tyndall Centre for Climate Change and Ricardo

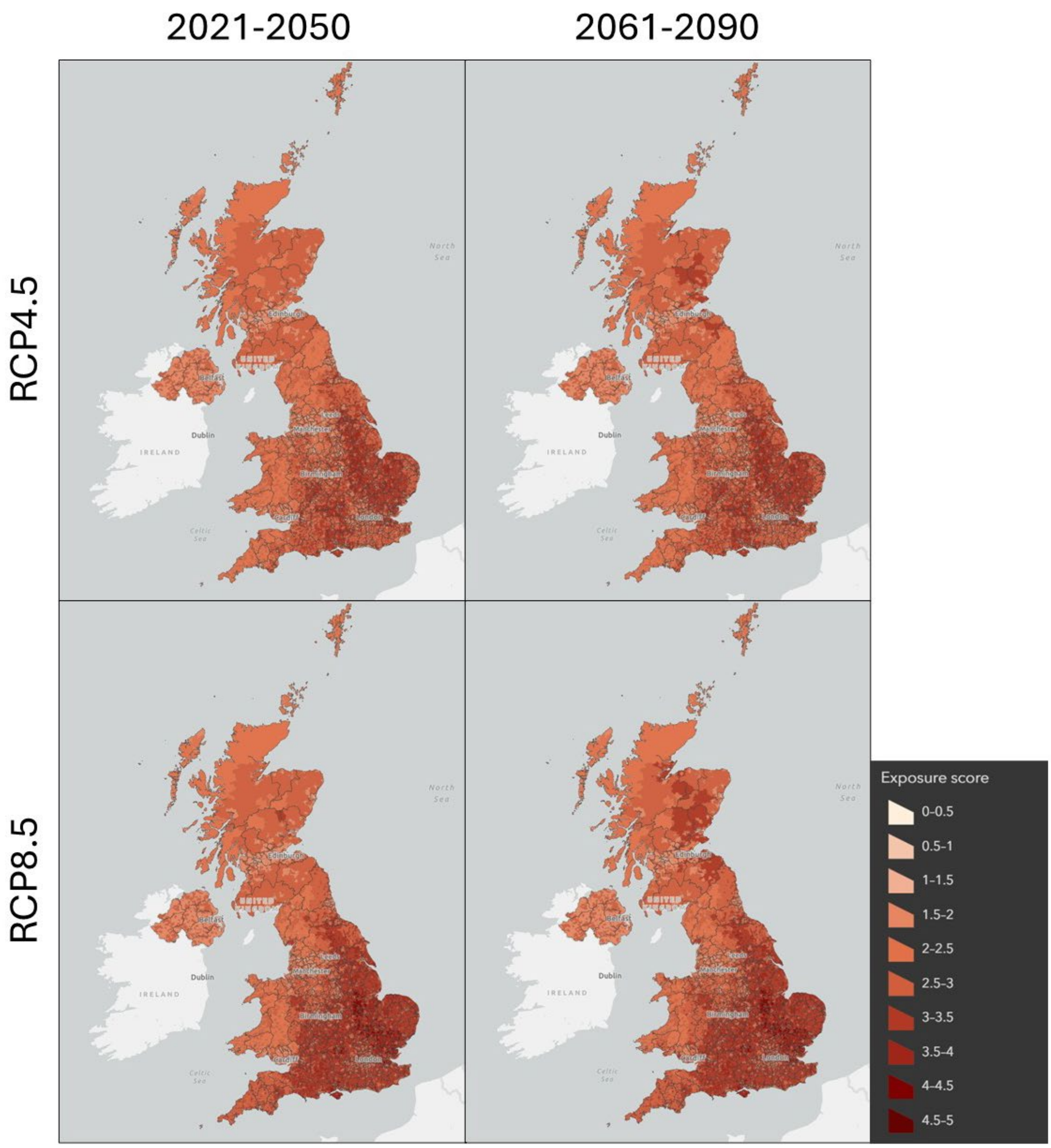
Summary of trends

Figure 5 Historical exposure to wildfires



In the recent past, a large proportion of the UK has faced relatively low exposure to wildfires, with most areas experiencing an exposure score between 1.5 and 3 (Figure 5). Cities have the lowest exposure, due to the lower proximity to vegetated areas. However, parts of the east Midlands, Norfolk, and other counties just north of London have been most exposed to potential wildfire occurrences with exposure scores of up to 3.5.

Figure 6 Projected exposure to wildfires



Under RCP4.5, the same spatial pattern of wildfire exposure is projected to occur but with a higher degree of exposure, and the addition of central southern England including Gloucestershire, Oxfordshire and Hampshire. This is projected in both future time periods of 2021-2050 and 2061-2090 (Figure 6). Under RCP8.5, in both future time periods, high exposure to wildfires is projected to occur across most of southern England excluding Greater London, the east Midlands, and further north in east Yorkshire. The highest exposure, with scores of between 4 and 4.5, is projected to occur on the Isle of Wight, parts of the east Midlands and in other counties just north of London.

Uncertainties, limitations and assumptions

The limitations associated with the analysis of wildfires include:

1. The methodology underpinning these results (detailed in Section A.3.4) is understood to be the first attempt to incorporate information about rural/urban and landscape factors into a system for rating wildfire exposure scores in the UK built environment. It has not been peer-reviewed, and projects such as the UK Fire Danger Rating System [H001] may at some stage provide a more rigorous system for rating exposure of the built environment to wildfire. The results presented here should be treated as preliminary, though grounded in theoretical bases that (i) certain land covers carry greater vegetation fuels and elevated potential for extreme fire behaviour (H002) and (ii) fire extent reliably correlates with fire weather in regions that are not fuel-limited (e.g. H003). We note that even comparatively fire-prone countries have rarely considered how projected shifts in fire-prone weather intersect with properties of the built environment or the wildland-urban interface, though methods have been developed and applied regionally for changes in fire-prone weather in the modern observational period (e.g. H004).
2. Scoring for the landscape factors is explicitly qualitative in nature and based on expert judgement of how fuel densities characteristically vary across land cover types or how the potential for fire spread varies across output area types with different rural/urban complexions. Improvements to the qualitative approaches would be to use quantitative summaries of fuel loads on UK land cover types to inform the ratings. Using empirical models of fire spread across the wildland-urban interface (WUI) in output areas with different rural/urban characteristics could also support more robust scores of wildfire exposure in different output areas. Since the initiation this project was completed, two new models of fuel stock densities have been developed with coverage of the modern era of satellite and meteorological observations (H005, H006). Projection of those models into future periods may provide scope for the improved quantification of the wildfire risks stemming from fuel load changes on a

spatial resolutions relevant to assessments of urban exposure, however this remains an active area of research.

3. Another assumption within this approach is the equal weighting of the landscape factor score and fire danger score in the overall wildfire exposure score (see eq. 2, Section A.3.4). This assumption is broadly in line with the theoretical basis of the landscape-scale fire triangle, which suggests that both fuel loads and fire-favourable meteorological conditions are required to create conditions suitable for wildfire [H007]. This could be developed into a more rigorous quantitative approach by modelling the historical co-variance between wildfire incidence in the WUI and landscape factor scores and fire danger scores. This is beyond the scope of the current project, given budget and timing constraints.
4. The rural/urban score and land cover score are fixed at modern values for future time periods and are not time-evolving. Projections of future UK urban expansion and land cover changes, which should be consistent with the socioeconomic pathways compatible with the RCP8.5 scenario, are not available at the time of this report's preparation. The static scoring of rural/urban score and land cover score is consistent with our assessment of future exposure for subsidence, where building data is fixed at modern values.

4.1.5 Pests

Introduction to hazard

Some pests are deemed by experts to be a potential problem in the future for the UK building stock due to changing climate conditions and rising average temperatures, through factors such as potential pest migration around and to the UK and enhanced development of species e.g. through potentially higher reproductive rates, or changes to the rates of pest mortality. The pests included in the analysis were selected through expert judgement and are presented in Table 5. This list is non-exhaustive due to a lack of historical observation records or available information on temperature thresholds for pests.

Table 5 Names of pest species

Latin species name	English species name
Hylotrupes bajulus	House longhorn beetle
Xestobium rufovillosum	Death watch beetle
Oligomerus ptilinoides	Bamboo powder post beetle
Attagenus smirnovi	Brown carpet beetle
Stegobium paniceum	Biscuit beetle
Anobium punctatum	Common furniture beetle
Coptotermes formosanus	Formosan subterranean termite

The historical, observed records of each pest species were sourced from What's Eating Your Collection [H008] and the NBN Atlas [H009]. This is point-data, showing the locations of approved/confirmed records of the different species, the results of which are presented in Figure 7.

The data used for the projections of pests is bias-corrected UKCP18 mean air temperature data, detailed in Table 6. This was sourced from the University of Bristol, and is daily data at a 12km² resolution, for both the 2°C and 4°C GWLs.

Table 6 Pest data details

Dataset name	Unit of measurement	Data file format	Spatial factors		Timeframes			Climate scenarios	Percentiles
			Resolution	Coverage	Interval	Historical data	Projections		
Bias corrected mean air	Degrees Celsius	NetCDF	12km grid	UK wide	Daily	Historical Tmean data not	Use of global warming	2°C and 4°C GWLs	Median of ensemble

Dataset name	Unit of measurement	Data file format	Spatial factors		Timeframes			Climate scenarios	Percentiles
			Resolution	Coverage	Interval	Historical data	Projections		
temperature (Tmean)						used (instead, point-data of historical records, see Table 15)	levels (GWLs)		

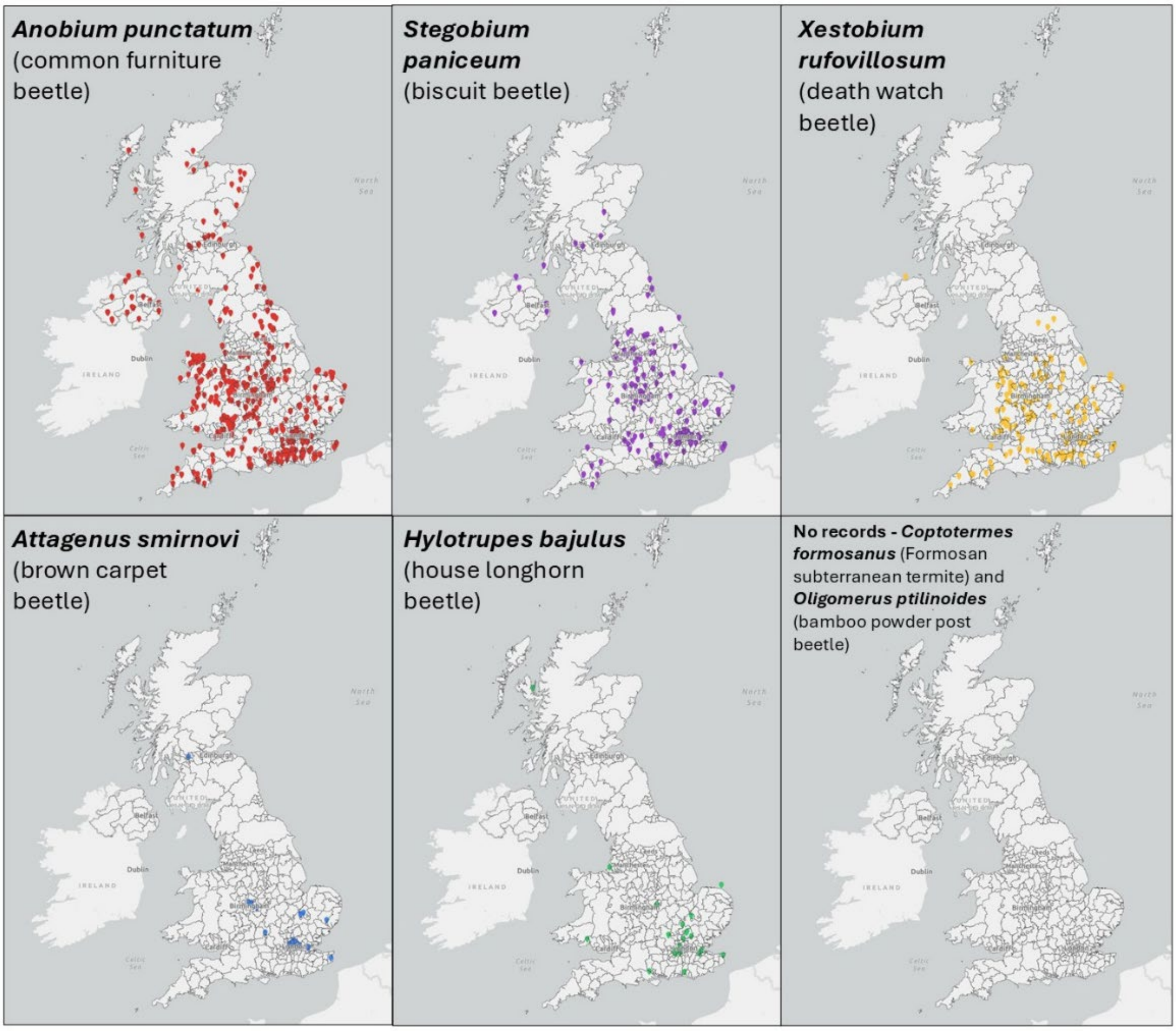
The exposure scores for pests were determined using two key factors: a. mean air temperature data, detailed above; and b. information about temperature thresholds for the development of specific pest species. In the case of the *Stegobium paniceum* (biscuit beetle), information on growing degree days (GDD) was also used to provide an indication of the exposure of buildings to that pest. The factors used to develop the exposure scores per species were dependent on the information available and are detailed in Section A.3.5. The thresholds for each species provide an indication of whether a location is projected to experience a temperature that can be associated with no, slow, or optimal development for a species at any stage of the life cycle, or temperatures that are high enough to potentially lead to pest mortality. This information was found through desk-research of academic literature and supplemented with expert judgement.

The results, shown in Figures 8 to 12, present the percentage of time i.e., the percentage of days per year, during which the mean air temperature is projected to sit within each temperature threshold, indicating the level of exposure to the different levels of pest development, per species.

Section A.3.5 contains details of the different thresholds per species, as well as more information around the use of GWLs, climate models, and the methodology for calculating the exposure information.

Summary of trends

Figure 7 Historical pest observations recorded between 1900-2024[9]



In the past, there have been observed records of most species excluding the Formosan subterranean termite and bamboo powder post beetle which are not currently present in the UK (Figure 7). Observations of the common furniture beetle and biscuit beetle span across

[9] Historical data shown here reflects *recorded* observations. Not all observations between 1900-2024 will be recorded accurately in the dataset.

the UK. The death watch beetle has been observed across England and Wales, with only one recorded observation in Northern Ireland, while there are fewer observations of the brown carpet beetle and the old house borer, both spread across England, with one record in Scotland and one record in Wales, respectively.

Figure 8 Projected percentage of days per year at the optimal temperature for development of the **house longhorn beetle, deathwatch beetle, and bamboo powder post beetle** (20-30°C) at GWLs 2 and 4°C

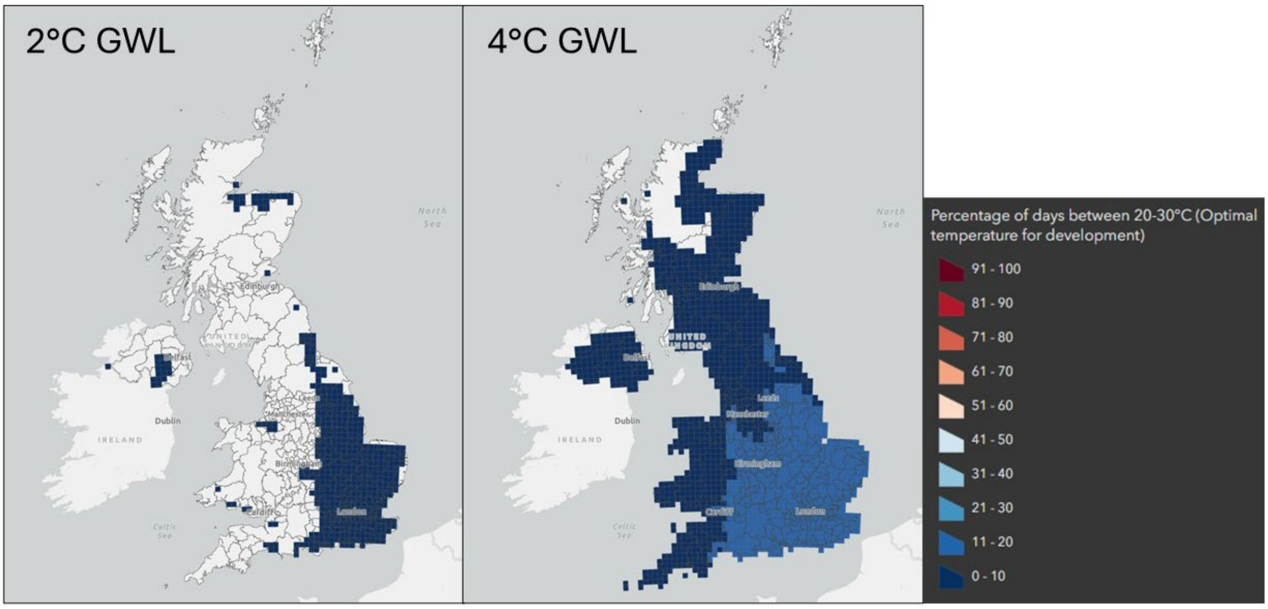


Figure 9 Projected percentage of days per year at the active temperature of the **Formosan subterranean termite** (9.3-38.1°C) at GWLs 2°C and 4°C

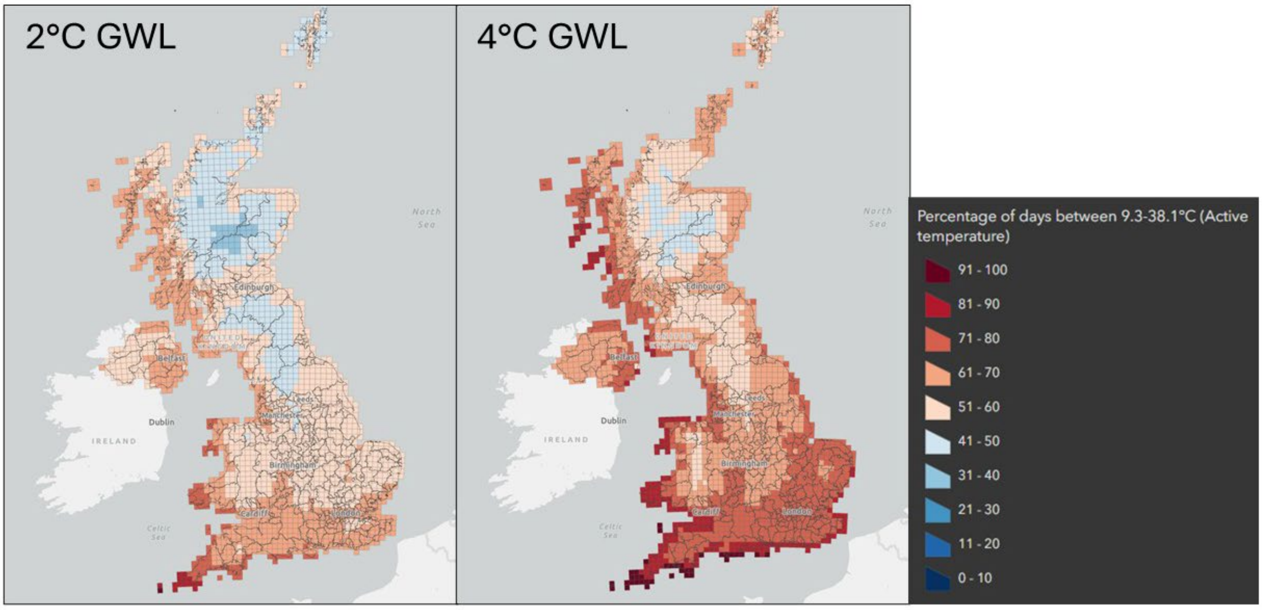


Figure 10 Projected percentage of days per year with daily mean temperature over 25°C, when flight occurs for the **common furniture beetle**, at GWLs 2°C and 4°C

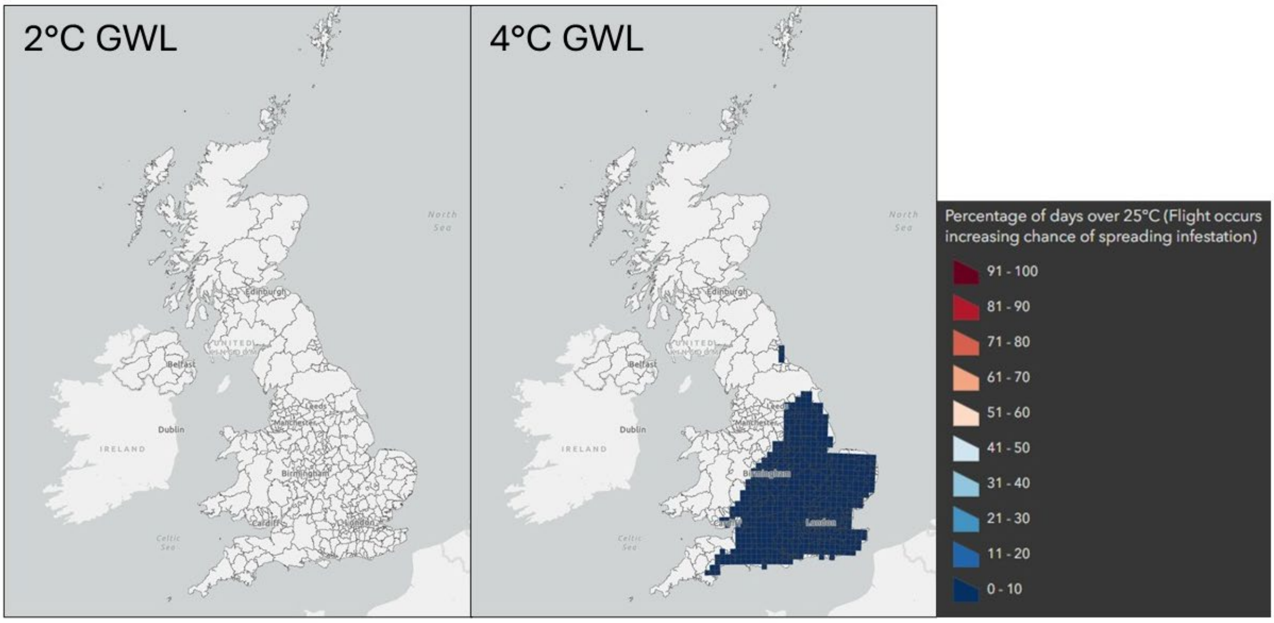


Figure 11 Number of life cycles per annum for the **biscuit beetle**, at GWLs 2°C and 4°C

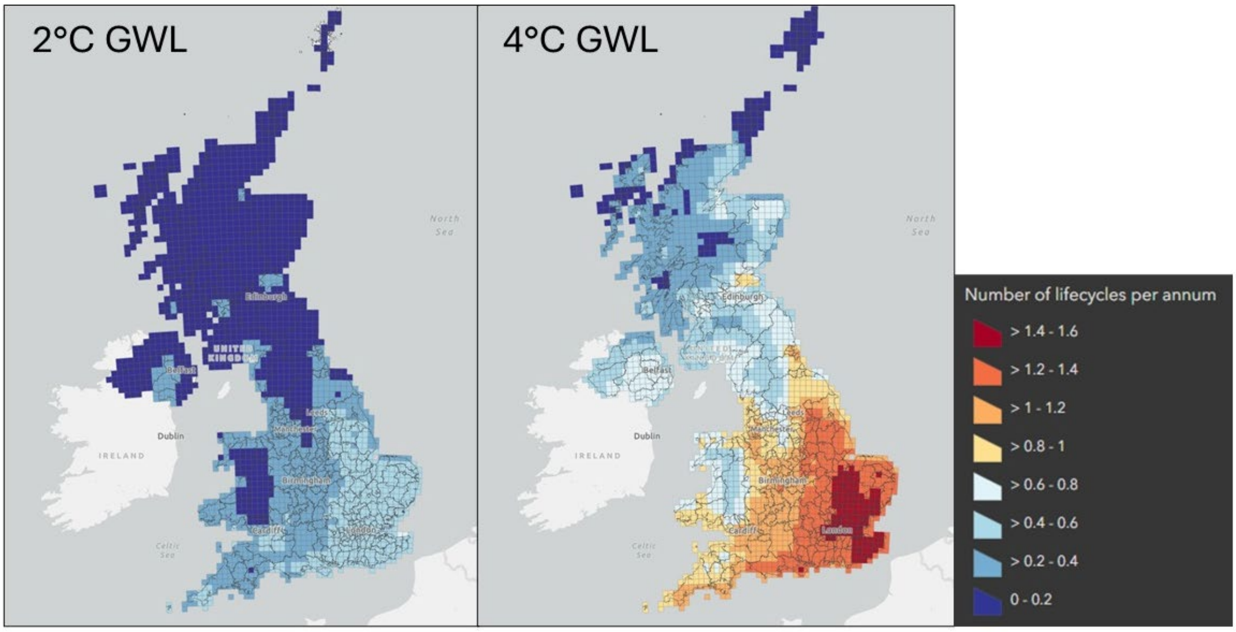
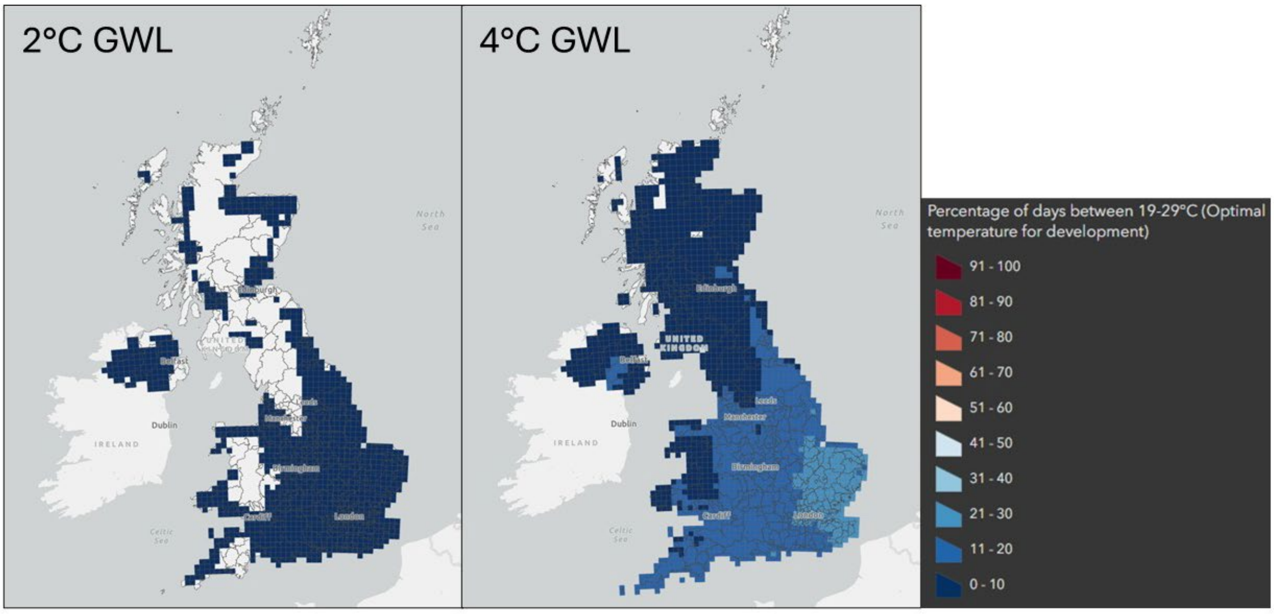


Figure 12 Projected percentage of days per year at the optimal temperature for development of the **brown carpet beetle** (19-[10]°C) at GWLs 2 and 4°C[11]



Figures 8 to 12 show projections of the temperature conditions that are optimal for the development of each species. In the future projections, there is a pattern of increasing pest exposure with higher warming, with southern and coastal areas generally projected to be more exposed. At the 2°C GWL, the east of England is projected to have low exposure to the optimal temperature range for the development of house longhorn, death watch and powder post beetles (Figure 8), while across England, particularly coastal areas and the southwest, there are projected to be a relatively high percentage of days per year at the active temperature of the Formosan subterranean termite (Figure 9). There is projected to be no exposure to conditions that would enable flight, and therefore increased spread, of the common furniture beetle at this GWL (Figure 10). Optimal conditions for brown carpet beetles are projected to occur throughout England, with parts of northwestern England, parts of Devon, Scotland, and Wales remain unexposed (Figure 12). At 4°C warming, exposure to optimal temperatures for house longhorn, death watch and powder post beetles is projected to expand across England, with high exposure in the southeast (Figure 8), mirroring brown carpet beetle patterns (Figure 12). Optimal conditions are projected across the whole of the UK for the Formosan subterranean termite is projected to reach all of the UK (Figure 9), while exposure to conditions that would enable a full lifecycle of a biscuit beetle, or more, projected to occur within a year, are isolated to the East Midlands and southern England excluding north Devon (Figure 11). The rest of the UK is projected to be exposed to conditions that can facilitate slower development of the biscuit beetle species, achieving a life cycle in longer than a year. Low exposure to increased flight, and therefore spread, of the common furniture beetle is projected in the east of England, with no exposure to spread elsewhere (Figure 10).

Uncertainties, limitations and assumptions

The limitations associated with the analysis of pest exposure include:

1. This methodology only considers mean air temperature as the underlying hazard data, while there are many other factors, both climatic and non-climatic, that influence

[11] The data underpinning this analysis is climate projections for mean air temperature; hence, the data being visualised is 'optimal temperature for development of the brown carpet beetle'. Where there is no data (i.e. white), there were no days identified as being between 19-29°C under the climate scenario.

pest development, potential migration and resulting exposure of buildings to pest infestations. Such factors include but are not limited to humidity, seasonal variations in air temperature, soil moisture levels, indoor temperatures, and GDD information for all species. These factors could be helpful to include in future analysis but were out of scope for this assessment due to timing and budget constraints and a lack of data availability for all species. In addition, the use of daily *maximum* air temperature may have been more appropriate for the analysis of *Anobium Punctatum* (common furniture beetle) instead of *mean* air temperature. The identified temperature threshold for this species (25°C) indicates when flight, and therefore spread, occurs, meaning the use of mean data does not show the full extent of when this temperature threshold is met, and hence the full extent of flight that may be projected to occur. Maximum air temperature data was not used in this analysis due to time constraints.

2. Another limitation of the use of mean air temperature data is that this only considers outdoor air temperatures. Indoor temperatures can also play a role in pest development, and the exposure of buildings to pests. For some species, indoor conditions play a bigger role than outdoor temperatures. However, this was not assessed due to a lack of available data, as well as timing and budget constraints.

3. There are some species that have been included that do not yet currently reside in the UK, meaning there are no historically observed records to present on the interactive map. These are *Oligomerus ptilinoides* (bamboo powder post beetle) and *Coptotermes formosanus* (Formosan subterranean termite). It is assumed that a) no record exists as they are not present in the UK given the current climate, as opposed to these species being present and their existence not being recorded, and b) a rise in mean air temperature alone across the UK may contribute to the migration of the species and result in increased potential exposure to buildings. However, there are multiple factors in addition to mean temperature change that contribute to the potential migration of pests (see point 1 above).

4. Unlike all other hazards, the historical data and projections for pests are presented differently to each other on the interactive map. The historical observations are point-data of the records of each species, while the projections are the temperature

threshold/GDD related exposure information. This is a limitation as it is inconsistent with the other hazards shown on the map and may reduce the visual comparability of past pest exposure to projected pest exposure. However, the hazard data can be approximately co-located or compared across the different map layers.

5. The pest species included is non-exhaustive, as there are some relevant species that may pose a challenge to the UK building stock in the future. Some other species were identified for the analysis but have been excluded due to a lack of historical observation records and/or available information on temperature thresholds for development and GDD, including but not limited to: *Lyctus brunneus* (powder post beetle); *Reticulitermes flavipes* (eastern subterranean termite); and *Zootermopsis nevadensis* (dampwood termite).

4.2 Sensitivity of buildings to climate-related hazards

To supplement the exposure assessment, this study conducted a Rapid Evidence Assessment (REA) of literature to extract evidence of building sensitivity to climate-related hazards. The purpose of the REA was to collate existing evidence and distil evidence gaps to support future in-depth analysis of climate risk to UK buildings. The study was unable to critically analyse evidence to generate a comprehensive mapping of building characteristics and vulnerability as the researching team did not include a buildings expert. This created limitations in the results as evidence was only extracted and not cross-examined or interpreted by experts within the wider context of knowledge regarding the built environment and climate-related hazards. There is also inconsistency within the literature regarding level and nature of sensitivity and risk associated with building characteristics and climate-related hazards. More research is required to identify and clarify these specific relationships. However, the identified evidence demonstrates that certain characteristics of a building (type, fabric, design, age) may affect the level of sensitivity, and therefore potential vulnerability and/or resilience experienced.

Below, key findings from the REA are presented to reflect on which building characteristics may contribute the level of overall building sensitivity to climate-related hazards. Full details of the methodology and results from the REA are presented in Appendix 1 .

4.2.1 Extreme wind

Table 7 High-level findings from review of evidence on building sensitivity to **extreme wind**

Description of potential building sensitivity	Contributing building characteristic			
	Type	**Fabric**	**Design**	**Age**
High winds can generate flying debris, such as roof tiles, which can become dislodged leading to damage buildings, windows, and building envelopes.	x	x	x	
Lightweight buildings (such as agricultural buildings, mobile homes and commercial trailers) are potentially more sensitive to extreme wind as they are unanchored.	x		x	
Roofs without continuous air barriers are prone to wind uplift, and roof damage can occur due to high suctions and pressure fluctuations, especially around peripheries and protruding sections like eaves. Traditional roof coverings like slates, clay tiles, and pantiles are particularly sensitive to water ingress in high winds, even when correctly installed. Simplified roof substrates are also sensitive to damage from extreme wind. Cladding on high rise buildings is sensitive through the same mechanisms.		x	x	
Traditional buildings or buildings with older materials can generally be more sensitive to extreme wind events as they can contain 'loose' materials (through means of deterioration or construction) which can become dislodged.	x	x		x

4.2.2 Wind-driven rain

Table 8 High-level findings from review of evidence on building sensitivity to **wind-driven rain**

Description of potential building sensitivity	Contributing building characteristic			
	Type	Fabric	Design	Age
Buildings that possess materials that are porous can be sensitive to moisture penetration and water ingress. The rate of absorption and desorption can influence the extent of damage. This can be affected by the construction materials, for example swelling and shrinking of timber which can results in faster deterioration.		x	x	
Water penetration occurs often through joints and connections within a building. Common outcomes of moisture damage include to leakage around windows and joints where moisture has penetrated beneath the insulation layer. This can be exacerbated by inappropriate material choice and fabric construction.	x	x		
Building age is not a consistent indicator for sensitivity to wind-driven rain. The sensitivity to erosion, water-ingress, and moisture damage is more often found to be related to building material, design, and quality of construction.		x	x	

4.2.3 Subsidence

Table 9 High-level findings from review of evidence on building sensitivity to **subsidence**

Description of potential building sensitivity	Contributing building characteristic			
	Type	Fabric	Design	Age
Earthen buildings are inherently sensitive to water infiltration and moisture fluctuations, leading to differential settlement and cracking.	x	x		
Cracking is a common consequence of subsidence, particularly in buildings with light, brittle structures.	x	x		
Traditionally constructed buildings respond differently to ground movement. Some are highly flexible and can adapt well to subsidence.	x			x
Buildings built on timber piles or rafts are sensitive to subsidence if the ground dries, compromising their stability.	x			x
Older buildings and buildings with shallow or no dug foundations are particularly sensitive to subsidence as the shrinkage and swelling of clay-based soil can cause more significant movement.	x			x
Long, dry spells can increase potential for increased thermal and/or subsidence cracking in masonry walls.			x	
Brick built buildings can be the structures most affected by shrinkage and swelling of clay soils[12].			x	

[12] There is inconsistency within the literature which examines the risk to buildings from clay shrink-swell subsidence, particularly regarding the age of brick-built buildings. Some evidence suggests that there is a decreasing trend of risk from subsidence throughout the 20th century, while others suggest that these 'older' buildings (when compared with modern buildings) are also at high risk. There is a lack of consistent definitions for the age of buildings considered 'old' or 'modern'.

4.2.4 Wildfires

Table 10 High-level findings from review of evidence on building sensitivity to **wildfires**

Description of potential building sensitivity	Contributing building characteristic			
	Type	Fabric	Design	Age
A number of materials used in construction are highly susceptible to ignition and rapid fire spread; for example, timber, expanded polystyrene (EPS), and aluminium composite panels.		x		
The buildup of leaves, embers, and other fuels in proximity to buildings or in gutters (or any valley/gulley geometric features), increases the sensitivity of buildings to wildfire ignition.	x	x	x	
Roofing materials like wooden shakes and shingles, or thatch, are potentially sensitive to firebrand ignition (ignition of new fires caused by embers from existing wildfires being transported by wind and landing on receptive fuel sources), making them particularly susceptible to wildfire damage.		x	x	x
Houses built with wooden roofs and floors are more susceptible to fire than reinforced concrete structures.		x	x	

4.2.5 Pests

Table 11 High-level findings from review of evidence on building sensitivity to **pests**

Description of potential building sensitivity	Contributing building characteristic			
	Type	Fabric	Design	Age
Timber framed buildings and timber materials, including facades, are particularly sensitive to insect infestations, especially termites.	x	x	x	x

Description of potential building sensitivity	Contributing building characteristic			
	Type	Fabric	Design	Age
Buildings with wood burning fireplaces, or that receive wooden objects e.g. furniture, or pallets could be more sensitive to pests, as they may enter the building in the firewood.	x			x

5. Evidence gaps and next steps

5.1 Evidence gaps

Throughout the study, specific evidence gaps have been identified in relation to the analysis of exposure. These are outlined below.

Projections of UK urban expansion and land cover change: There was a lack of quantitative projections of urban expansion and land cover change readily available for this study which limits the ability to integrate an understanding of the reality of the UK's future building stock under climate change. This study considers exposure through analysis of projections of climate-related hazards. However, in the case of subsidence, the hazard data is considered against available data on the existing building stock. While this will be improved with the addition of the NBD, to consider all climate-related hazards against building information, the use of existing (as opposed to projected) building data embeds an assumption that the future built environment will remain the same while climate change will continue to develop. This is untrue. Development of modelled scenarios of urban expansion and land cover change could help to broaden our understanding of potential futures, including impacts from future climate change on our future built environment. For example, understanding future exposure to wildfires is reliant on an understanding of potential future urban expansion and land cover change, as buildings currently at the boundary to vegetation are exposed, but exposure moves with the boundary.

Lack of historical pest records: The list of pests considered in this study are non-exhaustive. Some relevant species may pose a challenge to the UK building stock but have not been analysed due to a lack of historical observation records and/or information relating to temperature-mortality thresholds and GDD.

5.2 How to use this information

The Hazard Mapping Visualisation tool can be used to identify regions that are projected to be particularly exposed, or not, to climate-related hazards, or to identify the level of exposure in specific areas/local authority regions of interest. It should be used as a starting point to help inform analysis of impact and/or risk to the built environment from the five climate-related hazards assessed in this study (described further in Section 5.4). The tool provides a visualisation of the spatial distribution of sensitivity of the built environment to subsidence, and exposure to the remaining hazards. This information should be combined with further qualitative information on the vulnerability (sensitivity and adaptive capacity) of the UK building stock, and the location/distribution of buildings to identify what buildings are actually exposed, to inform any potential decision making conducted using the information presented in the tool.

5.3 Recommendations for tool improvement

Updates to the underlying data within the interactive maps are planned for 2025, specifically the addition of DESNZ's National Buildings Database (NBD), which is currently under development. Once finalised, this will add substantially more detail to the non-domestic building information presented within the maps, including building activity classification and building characteristics (size, age, construction, and energy performance). With the additional detail from the NBD, users will be able to identify specific buildings and areas which are highly exposed to the climate-related hazards, improving the starting point for further analysis of vulnerability, impact and/or risk to buildings.

Improvements could also be made to underlying climate-related hazard data, specifically:

- **Subsidence (clay shrink-swell):** The subsidence data used in this study is available in two formats, GeoClimate Open and GeoClimate Premium. This study utilised GeoClimate Open, which is designed for use in national overview analysis, while Premium is designed to provide further detail. The use of Premium would increase the spatial granularity; however, it is licensed with a payment for access. For more information see Section A.3.3.1.

- **Wildfires:** Improvements to the qualitative approaches of assessing exposure to wildfires, regarding landscape factors, would be to use quantitative summaries of fuel loads on UK land cover types to inform the ratings. Using empirical models of fire spread across the wildland-urban interface (WUI) in output areas with different rural/urban characteristics could also support more robust scores of wildfire exposure in different output areas. Significant additional research would be required to develop the qualitative approach of assessing exposure to wildfires, based on landscape factors, into a quantitative and systematic peer-reviewed approach. Exchange with the UK Fire Danger Rating System [H001] would be required to understand unpublished progress and avoid parallel efforts.
- **Pests:** This study only considers the mean air temperature as the driving parameter for pest development. Better accuracy could be achieved by also considering humidity, diurnal and seasonal variation in air temperature, soil moisture levels, as well as non-climatic factors such as indoor temperatures, GDD information, and the distribution and migration of potential predators of pests. The pest analysis could further be developed by developing a baseline using the air temperature data and any other parameters that may be used to determine projections. This would enable more direct comparison between historical pest information and the projected outcomes. For more information see the uncertainties, limitations and assumptions in Section 4.1.5.
- **Use of climate models:** The median climate model i.e., the individual model that produced the median projected output in the ensemble, has been used for the projections shown on the map. This can be built upon in future iterations to also include the minimum and maximum climate model outputs, to acknowledge the range of potential outcomes and acknowledge uncertainty between the outputs of the UKCP18 climate models.

5.4 Opportunities for further research

While this study provides an initial basis for understanding sensitivity and exposure of the UK's building stock to climate-related hazards, further research could use the information to generate a full assessment of climate-related impacts and risks, aligned with the

Intergovernmental Panel on Climate Change’s (IPCC) terms and their interactions. This could first consist of identifying vulnerability of the UK building stock to the five climate-related hazards, which would require identification of adaptive capacity, in the context of the already identified sensitivities. The vulnerability assessment could then be combined with the existing spatial exposure assessment to identify priority areas of the UK which are *most* vulnerable and *most* exposed to progress to a detailed impact assessment.

Appendix 1 – REA of building sensitivity

A.1.1 Overview and purpose

The main output of this study is an interactive map that presents the exposure of the UK building stock to five climate-related hazards (extreme wind, wind-driven rain, subsidence, wildfires, and pests), in the recent past and projected under different future climate scenarios. The purpose of Task 1 was to provide a supplementary qualitative analysis, finding the sensitivity of building characteristics (type, fabric, design, and age) to these hazards, to supplement the spatially mapped results.

Task 1 consisted of a Rapid Evidence Assessment (REA) to gather information on the sensitivity of different building characteristics within the UK to five climate-related hazards. This lays the groundwork for a future "deep dive" on the vulnerability of different building types and fabrics that the Energy Research Team is aiming to begin next year. Project partners[13] provided a list of preliminary relevant building types and fabrics to include in the analysis. The geographical scope of the review was UK-wide, as was the remainder of the analysis for this project. Some relevant data from outside the UK was however identified and used, when appropriate.

This assessment was based on the definition of sensitivity contained in the IPCC's Sixth Assessment Report (AR6: WGII Glossary). This ensured comparability with similar assessments conducted within the UK and internationally.

Sensitivity: The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Sensitivity, rather than vulnerability, was assessed as it was not possible to undertake an analysis of adaptive capacity within the timeframes of this project. An assessment of adaptive capacity typically requires, for example, stakeholder interviews to understand

[13] Tyndall Centre for Climate Change Research, University College London, and British Geological Society

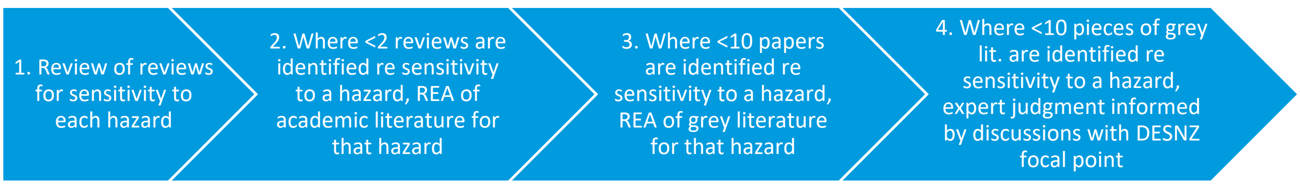
organisational, financial, and technical capacity. In the context of this project, it would also be necessary to conduct an assessment of heritage significance for designated buildings or those in conservation areas, as many buildings sit within these categories. This was not possible under this study and is recommended for consideration in future research on building vulnerability and risk from climate-related hazards to the building stock.

A three-tiered approach was followed. Initially a “Review of Reviews” was undertaken, regarding the sensitivity of relevant building types and fabrics to climate-related hazards using pre-defined search terms. Where at least two relevant review papers were identified, this formed the evidence base for understanding sensitivity to that climate-related hazard for the purposes of the remaining tasks in this project.

Where less than two relevant reviews were identified by the search, a Rapid Evidence Assessment (REA)[14] was undertaken to identify additional evidence regarding sensitivity to the particular climate-related hazard. This began with a search of the available academic literature. However, where less than ten relevant papers were identified by the search (after screening of the results), an REA of the available grey literature was undertaken to identify further evidence.

Where less than ten relevant pieces of grey literature were identified regarding sensitivity to a climate-related hazard (after screening of the results), sensitivity was assessed based on the research team’s expert judgment, in discussion with DESNZ colleagues and key industry stakeholders.

The methodology used for the Review of Reviews, REA, and expert judgment is set out below, and summarised in the below figure.



[14] See Collins, A., Coughlin, D., Miller, J. and Kirk, S. (2014) The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide, Joint Water Evidence Group, Defra. Smithers, R.J. (2015) SPLiCE Phase 1: A methodology for Rapid Evidence Assessments. Report for Defra.

The research team engaged closely with related work that DESNZ is currently undertaking and planning, to ensure the results of the light-touch, rapid assessment can support and align with this work to the extent possible.

Sub Task 1.1: Identify relevant search terms

Primary-tier search terms specific to each climate-related hazard within the scope of this project and related to relevant building fabrics and types were identified. These were shared with the DESNZ focal point for review and comment, and were developed in an iterative manner, with test searches informing edits to search strings to ensure high quality results. The searches were performed in Google Scholar, with use of the AND, OR, " ", and * search operators to refine the results.

The finalised primary search terms, were as below:

Building type: *Domestic OR home OR dwelling OR non-domestic OR residential OR commercial OR retail OR industrial OR "park home" OR "mobile home" OR (static) caravan OR bungalow OR terrace* OR flat OR maisonette OR semi-detached OR detached OR factory OR warehouse OR store OR shop OR "public* building*" OR Portacabin OR Terrapin OR "place* of worship" OR barn OR office* OR Mansion OR Palace OR Castle OR penthouse*

Building fabric: *insulation OR flammab* OR glazing OR cladding OR "waterproof* coat*" OR lead OR lime OR brick OR block OR stone OR slate OR thatch OR timber OR cement OR concrete OR clay OR mud OR mortar OR earthen OR sandstone OR limestone OR granite OR whinstone OR cob OR OR masonry OR metal OR plaster OR plastic OR composite OR glass OR Iron OR felt OR alumin*um OR copper OR asbestos OR flint OR render OR zinc OR steel OR lead OR tin OR putty OR wool OR woodfibre OR kingspan OR bitumen OR asphalt OR tar OR ceramic OR terracotta OR fibreglass OR board OR fibreboard OR plywood OR "wall*paper"*

Building design: *ventilat* OR drainage OR tile* OR roof* OR wall* OR foundation* OR footing* OR window* OR EPC OR "energy performance certificate" OR door* OR floor* OR room* OR hallway* OR passageway* OR corridor* OR aisle* OR fireplace* OR lintel* OR electric* OR mechanical OR heating OR "trench fill" OR basement* OR cellar* OR balcon**

OR conservatory OR stair OR lift* OR elevator* OR escalator* OR porch* OR garden* OR steeple* OR tower* OR veranda* OR shaft* OR boiler* OR "heat pump*" OR "solar panel*" OR turbine* OR chimney OR arch* OR apse* OR column* OR colonnade* OR frame* OR truss* OR vault OR "green roof*" OR "living roof*" OR "green wall*" OR "living wall*" OR "rain*screen" OR facade*

Building age: *"Building* age" OR "construction age" OR "building period" OR historic OR Georgian OR Victorian OR Edwardian OR modern OR post-war OR Roman OR Medieval OR Tudor OR Stuart OR Hanover* OR "traditional construction" OR "modern construction" OR modular OR listed OR "conservation area*" OR jacobien OR baroque OR "inter*war"*

Secondary-tier search terms related to sensitivity were also identified. For consistency, the sensitivity-related search terms used were those in CS-N0W Work Package E2 (WPE2) on adaptation/mitigation co-benefits and trade-offs and the ad hoc project reviewing the resilience of the NZIP, with the addition of *hazard, variability and adaptation*.

The final search string used was: *("climate change") AND (risk OR vulnerability OR sensitivity OR resilience OR hazard OR variability OR adaptation).*

Tertiary-tier terms were then used to screen for those results on the 5 climate hazards being investigated.

Extreme wind: *high wind* OR severe wind* OR wind storm* OR windstorm* OR wind chill* OR wind speed* OR storm track* OR Extreme wind* OR Cyclone OR Tornado OR Typhoon OR Hurricane OR Wind gust* OR wind load* OR wind direction* change* OR wind pattern* change OR wind transport pattern* change*

Wind-driven rain: *wind-driven rain* OR wind-driven precipitation* OR horizontal rain OR horizontal precipitation OR rain horizontal velocity*

Subsidence: *subsidence* OR Land sink* OR Ground sink* OR Shrink-swell OR Swell-shrink OR Shrink* OR Swell* OR Heave OR Ground movement* OR Land movement* OR Expans* soil* OR Expans* clay OR Crack* ground OR Foundation movement* OR Coast* subsidence OR Urb* subsidence OR Lowland subsidence OR soil desiccation*

Wildfire: *fire weather* OR wildfire* OR Bushfire* OR Forest fire* OR Rural fire OR Urban fire OR uncontrolled fire*

Biological hazards (pests): *new pest* OR novel pest* OR invasi* specie* OR range* pest* OR distribut* pest* OR Wood borer* OR Termite* OR Furniture beetle* OR Anobium punctatum OR Woodworm OR Death watch beetle* OR Xestobium rufovillosum OR Oligomerus ptilinoides OR Wood weevil* OR Euophryum confine OR Pentarthrum huttoni OR Longhorn beetle* OR Hylotrupes bajulus OR Powder post beetle* OR Lyctus sp. OR Bostrychid borer* OR Wharf borer* OR Nacerdes melanura OR Carpenter ant* OR Camponotus sp. OR Lasius brunneus*

As the geographic focus of this study was the UK, evidence related to the UK or similar geographies (or global studies that include the UK) was more relevant than evidence from other geographies. When initial searches (before screening) produced more than 100 results, a location filter was proposed to be applied to prioritise the most geographically relevant results: (global OR Eur* OR temperate OR Great Britain OR Brit* OR United Kingdom OR UK OR Eng* OR Wales OR Wel* OR Scot* OR Northern Ireland OR Northern Irish). In practice, this issue did not occur, and these search terms were not used.

The results of these searches were recorded in a comprehensive Excel workbook, including the author(s), year, title, and source (including hyperlink where available), and relevance to keywords for each paper identified. This ensured ease of access across users (including those involved in other work across DESNZ on sensitivity in the built environment) and simplifies any future updates to the research to incorporate more recent evidence.

Sub Task 1.2: Screening the results

The results were screened for relevance based first on title and then on abstract. Screening of all evidence was undertaken by one person per climate-related hazard to ensure that the criteria were applied consistently. A second technical expert independently screened a 10% sample of the evidence per climate-related hazard to check that there were no biases.

As the “Review of Reviews” was found to be insufficient for all the hazards following the approach outlined above, an REA of the available academic literature was performed by searching Google Scholar to identify relevant papers.

Sub-task 1.3: Extract evidence

Evidence was extracted from the documents arising from the searching and screening, as relevant to the sensitivity of relevant building types and fabrics to the climate-related hazards being assessed, including key information such as the scale of study, location, key messages, caveats, etc.

While extracting evidence, some additional documents were identified to be added to the review based on "snowball sampling" –where another highly relevant document is cited in the document being reviewed. When these cited documents filled gaps in the evidence regarding sensitivity of a relevant building type/fabric to the climate-related hazards being assessed, the cited document was added to the review, noting in the evidence extraction spreadsheet that the document was identified through this snowball sampling process.

In addition, at this stage the wider project team and experts also used expert judgement to include additional highly relevant papers which filled gaps in the current evidence base. This ensured that highly relevant evidence was not excluded from the analysis merely because it did not appear in the search results. Examples of circumstances where highly relevant literature was included manually and not identified through the REA process included where different terminology was used, publication in a database that was not readily accessible, or literature awaiting publication. The DESNZ focal point also provided relevant evidence known to them to be included in the assessment.

The evidence extraction process used is summarised below:

Table 12 Evidence extraction process and information extracted

Stage in process	Evidence added to the summary table
Searching for evidence	Author(s), Title, Hyperlink, Date, Source, Relevant keywords
Screening the search results	Removed during title screening (y/n) Removed during abstract screening (y/n)
Extracting the evidence	Literature type, Scale of study, Location, Key messages, Caveats

A.1.2 Results

This section provides an overview of the key sensitivities of buildings to the five climate-related hazards: extreme wind, wind-driven rain (WDR), subsidence, wildfires, and pests. The analysis is organized into five tables, each reflecting key sensitivities per climate-related hazard and the building characteristics that contribute to the sensitivity.

A.1.2.0 Extreme wind

Table 13 Key sensitivities of building categories to extreme wind

Category	Key sensitivities to extreme wind
Building type	For **urban settlements in developed (high capacity) economies** there is direct or strong research evidence that moderate/high impacts on buildings, infrastructure and populations are associated with windstorms (T3). **Agricultural buildings, mobile homes and commercial trailers,** being lightweight and often unanchored, are highly sensitive to high winds and usually suffer the most damage (T95). An exception to this may be container houses as they are made of material designed to bear heavy wind loads. Their structural stability makes them particularly resistant to extreme winds (T43). Evidence from the hurricane-prone Florida coastline shows that **houses without a continuous structural element** and firm connections with their foundations are more sensitive to storms (T14).
Building fabric	Traditional **roof coverings like slates, clay tiles, and pantiles** are particularly sensitive to water ingress in high winds, even when correctly installed (F026). **Curtain wall building fabric** can be sensitive to extreme wind; this is determined by the structural integrity of the aluminium framing and load-bearing capacity of the infill panels (F008). "Materials such as **masonry or concrete** that are well tied to all other building components have a **higher chance of surviving high winds** associated with tornados. The weight of these materials will **help resist uplift and lateral loads**. **Lightweight roofing and siding** materials like gravel and insulation, shingles, and brick veneer, and roofing membranes **could become debris**." (F007)

Category	Key sensitivities to extreme wind
Building design	**Roof systems without continuous air barriers** are sensitive to wind uplift, and roof damage can occur due to high suctions and pressure fluctuations, especially around peripheries and protruding sections like eaves (F026). Damage to **roofs** is caused by local high suctions and large pressure fluctuations around the roof periphery and protruding portions such as **eaves**. Local roof damage can lead to total roof destruction (D46, 58). Buildings **experience positive pressure on windward faces** and negative pressure on leeward sides/corners (F001). Damage to **tile roofs** increases as the substrate is simplified, meaning that reducing its weight by removing roofing cement **creates openings between the substrate and tiles.**. If there is insufficient rustproofing of nails and steel wire, they lose their strength within a few years and thereafter cannot fulfil their original function (D46, 58). Most damage to **corrugated metal roofs** is induced by local suction at the **eaves and periphery** (D46). If a roof has **protruding parts** like **short chimneys, skylight roof windows, and dormer windows**, the flow over the roof surface is locally disturbed, sometimes producing local high suction and turbulence (D46). There is often insufficient consideration of the wind resistance of **rain gutters, spoutings, verges and copings** in roof peripheral areas, where local wind pressures become large. Damage to these lightweight members may trigger large-scale damage to roof cladding, leading to total roof destruction (D46). **Window panes** have the potential to be damaged by wind pressure or wind-borne debris. Furthermore, the impact of wind-borne debris on building envelopes at high speed is one of the major risks related to powerful storms (D46, 48, 57).
Building age	Strong winds can cause surface erosion over time such as alveolation (A2, A39, A44, A54). "**Complex roofs of historic houses** make them especially vulnerable to wind damage." (A3, A96). However, many buildings possess complex roofs which can increase susceptibility to wind damage; this is not solely determined by age. "Damage occurs to buildings that have not been built to comply with **existing codes** and which have **not been well maintained** subsequently" (A5).

Category	Key sensitivities to extreme wind
	"Houses built to **new regulations** suffered little damage. **Older buildings** often had roofing removed frequently with battens still attached." (A7). Bell towers on churches are vulnerable to wind damage which can lead to the whole bell tower collapsing in high winds (A14) Where **buildings** have **not been well maintained**, extreme wind will accelerate decay of worn and week elements. "Continued neglect can lead to structural movement and eventual failure" (e.g. collapse of chimney stacks and gable ends). 76% of **traditional houses** in Scotland need repairs to "critical elements" (A30, A32, A42). Damage from falling trees is also of concern especially to **historic buildings** where trees are often planted nearby (A39, A66).

A.1.2.1 Wind-driven rain

Table 14 Key sensitivities of building categories to wind-driven rain (WDR)

Category	Key sensitivities to wind-driven rain (WDR)
Building type	Where full-fill cavity wall insulation has been retrofitted in locations experiencing wind-driven rain, damp can occur as the insulation retains water that penetrates the façade, and can bridge moisture into the inner leaf (T170). "Increased frequency of wind driven rain may result in an increase of abrasion and dissolution rates in buildings. Wind-driven rain leading to the erosion of **sandy brick construction** is already a problem for the **National Trust property of Blickling Hall, Norfolk**. Historic Scotland identified increased rainfall as a particular threat to **semi-ruinous buildings** due to water penetration through wall-heads" (T74). WDR is a source of moisture that can drive swelling and shrinking of timber which can result in cracks and further deterioration (T158).
Building fabric	**Limestone** is particularly sensitive to WDR because WDR can lead to damage from surface erosion. This is evident in cases like the Cathedral of Learning in Pittsburgh, where high WDR areas corresponded to eroded white patches on the limestone walls (F012). Droplets from WDR may spread, splash, or rebound and can form a water film that runs down the façade of limestone walls (F035).

Category	Key sensitivities to wind-driven rain (WDR)
	Monumental brick masonry can also suffer WDR erosion, as reported in St Hubertus, Netherlands (F012). Moisture penetration depth depends on coating type and external climate (F033). **Earthen walls** are highly sensitive to WDR due to direct raindrop impact and abrasion (F012). **Porous materials**, including many traditional building elements, are generally more sensitive due to their high moisture absorption rates (F015, F016). The rate of absorption and desorption can influence the extent of damage (hysteresis). Different compositions (e.g., old vs new bricks, various mortars) have varying sensitivity (F015). **Historic Masonry Infilled Timber Frames,** being porous, are susceptible to water infiltration from WDR. This weakens the timber frame, making the structure more prone to wind damage (F017). **Capillary-active insulation materials,** such as calcium silicate, and thinner insulation assemblies generally experience lower moisture levels under WDR (F025). **Material properties such as bond strength, porosity/tortuosity and surface roughness, i**nfluence the sensitivity of building fabric to WDR. Weaker bonds between particles in the material make it easier for WDR to detach them, porosity/tortuosity influences how deeply water penetrates, and rougher surfaces are more prone to particle disturbance from raindrop impact compared to smoother ones (F012). **WDR exacerbates various weathering processes**, including chemical, freeze-thaw, salt, and biological weathering, particularly in the case of **stone, mortar, masonry and concrete)** (F016, F018).
Building design	Rainwater penetration is particularly evident through **joints and connections**. The main reasons for moisture damage are generally **leaks around windows and joints** where rainwater has penetrated past the facade. Other WDR sensitivities due to **design defects** include **gutter fissure and masonry interface**, either on vertical or horizontal masonry surfaces, **window-wall junctions, duct and cable junctions** and **terrace doors level with the terrace** (D18, 37, 38).

Category	Key sensitivities to wind-driven rain (WDR)
	"WDR potentially **keeps the façade materials damp for longer periods of time** and the **moisture gets below overhangs more easily**… Wind driven rain is threatening to structures if they are **not covered and ventilated sufficiently** to allow for drying" (D31). In newer or more modern construction, **drained wall systems** are widely recommended as a best strategy for controlling rain penetration inset into the wall, as the window's face has greater protection (D5). The **lower section of a façade** often shows more water-related damage than the top, because water draining down, coupled with slower evaporation (less wind and incident solar radiation) keeps the bottom wet for some time (D18). A **sloping wall** will experience a lower load of wind-driven rain than a vertical wall (D17). **Highly insulated modular panels** installed onto the existing concrete wall will increase relative humidity behind the insulation (D4).
Building age	Studies specifically exploring heritage buildings show that **cultural heritage** buildings are sensitive to surface erosion as external fabric may "face greater weathering action" (A2, A5, A53, A54). Similar heritage studies also show that WDR can lead to damage to surfaces of **historic buildings**, causing "severe surface deterioration" which eventually leads to "structural integrity loss", when in combination with high winds (A15, A25, A49, A62). However, this is dependent on the specific building materials in use. Studies in Finland have highlighted the vulnerability of **post 1970** concrete buildings to corrosion caused by WDR (A57). Many **older buildings** have detailing that can protect the façade from water damage. (A5) In more **modern buildings** that lack this detailing staining can occur on the walls, especially for concrete structures. "Some early **20th century buildings** feature parapets with no protective drip detailing. This invariably causes problems in all but the most sheltered locations" (A30).

Category	Key sensitivities to wind-driven rain (WDR)
	Several research studies have shown that WDR directly affects the moisture content of **historic envelopes**", WDR is also the dominant factor determining the moisture movement in walls. This increases the risk of mould growth (especially in **historic wooden buildings**) and moisture related damage (A36, A37, A42, A49, A56, A59, A63, A67). This in combination with other factors in **cultural heritage buildings**, "could even undermine the structural integrity and stability of building components" (A56) Buildings that do not comply with **current building codes** and which have **not been well maintained** have cracks in their façade or unsealed/ exposed joints (A5). "Driving rain increases the moisture content of walls aggravating deterioration of the fabric and increasing penetration through joints, door and window frames" (A5).

A.1.2.2 Subsidence

Table 15 Key sensitivities of building categories to subsidence

Category	Key sensitivities to subsidence
Building type	UK buildings on **clay rich ground** are particularly sensitive to shrink-swell action. "The drying out of certain geologies (e.g. clay) can increase subsidence affecting structures" (T36). In the UK, some Mesozoic and Tertiary clay soils and weak mudrocks, including the London Clay, are susceptible to shrinkage and swelling as environmental conditions change. These volume changes can cause enough ground movement to damage the foundations of some **light structures** such as **houses** (T102). **One or two-story buildings, residential properties and other low-rise buildings are particularly sensitive** to subsidence as they are relatively light structures and are therefore less capable of resisting the differential heave caused by swelling soils compared to heavier multistorey buildings (evidence from the US) (T120, T168). **Buildings with shallow or no dug foundations, more commonly seen in older buildings,** are particularly sensitive to subsidence. Factors that exacerbate the risks of subsidence for

Category	Key sensitivities to subsidence
	homes include prolonged hot spells which dry out the soil, removing moisture which impacts the building's structure (T164). Most damage from ground movement occurs on **relatively small buildings** such as **one-to two-storey buildings** (F097). **Traditionally constructed buildings** respond differently to ground movement. Some are highly flexible and can adapt well to subsidence, while others rely on their large footprint to distribute the load and mitigate the impact (Input from project steering group). **Buildings near trees** can be more sensitive to subsidence, as the trees remove moisture from the ground (T164, T3). However, there is uncertainty about vegetation responses to climate change. Different tree root systems can remove moisture from the ground, leading to shrinking soils and affecting building stability, but they also serve to soak up excess water, which can prevent swelling, highlighting key trade-offs. The responses are also largely dependent on the type of tree (inputs from project steering group).
Building fabric	**Earthen materials** are inherently vulnerable to moisture fluctuations, leading to potential slumping of walls. Common damage patterns include erosion of the upper wall sections, cracking, and undercutting at the base due to water infiltration and salt ingress (F083).
Building design	Shrinkage and swelling of clay soils is the single most common cause of **foundation-related damage** to low-rise buildings in the UK. Seasonal shrinkage and swelling will be a major factor of concern if climate change produces drier summers and wetter winters, because, as predicted for the UK, shrinkage during periods of drought causes the greatest degree of damage. There is evidence from France that soil conditions are becoming progressively drier and this is consistent with a long-term drying trend predicted for the UK (D63, 65, 69, 73, 74). Long dry and windy spells can increase potential for increased cracking in **masonry walls** (D63). **Southern façades** of buildings have longer exposure to sun, leading to greater desiccation and shrinkage of clay soils (D69). **Brickwork buildings** are the structures most affected by shrinkage and swelling of clay soils (D69).

Category	Key sensitivities to subsidence
Building age	"Typically, the structures that experience problems with expansive soils are **older homes**, but **newer homes** (built within the last 15 years) may also experience problems due to expansive soils" (T120). Heritage managers expressed "some concern about changes in soil moisture content leading to subsidence and heave affecting **buildings and ruins**" (A3). Subsidence can cause "structural damage to **heritage buildings**, including settlement of foundations, cracking, and accelerated decay of masonry" (A39, A77). "Many properties such as churches, wind-pumps and water mills were built on timber piles or rafts, which are stable only as long as they are kept wet; drying of the ground will therefore affect their integrity" (A5). "In Andalusia, shrinkage –swell damage far exceeds earthquake damage". This is particularly evident for some **heritage buildings** in the area which have had to be underpinned or reinforced (A73). Evidence from CCRA 2 suggests that **older buildings** and buildings with shallow or no dug foundations are particularly sensitive to subsidence. Factors that exacerbate the risks of subsidence for homes include prolonged hot spells which dry out the soil, removing moisture which impacts the building's structure (T164). **Traditionally constructed buildings** respond differently to ground movement. Some are highly flexible and can adapt well to subsidence, while others rely on their large footprint to distribute the load and mitigate the impact (Input from project steering group).

A.1.2.3 Wildfires

Table 16 Key sensitivities of building categories to wildfires

Category	Key sensitivities to wildfires
Building type	All building types in rural areas, including **homes, offices and industrial facilities**, are sensitive to wildfires (T138).

Category	Key sensitivities to wildfires
Building fabric	Materials like **timber**, **expanded polystyrene** (EPS), and **polyurethane** (PUR) are highly susceptible to ignition and rapid fire spread (F004, F062, F068). For timber, the formation of a **char layer** during combustion acts as a protective barrier (F060), however, effectiveness of this protection depends on timber **thickness, density and heat flux** (F065). **Combustible roofing materials**, such as **thatch or wooden shakes and shingles**, are particularly vulnerable to **firebrand ignition** (embers carried by wind) (F063). Thatch fires are almost impossible to control, hence prevention is essential (F099). In particular, fire spread due to ejected window flames must be considered in case a thatched roof is near a neighbouring house (F098). Combustible **cladding** materials, like **timber** and certain **aluminium composite panels** (ACPs) (F065, F073), increase the risk of ignition and fire spread. Materials with **high flame spread indices** (FSI), or those that **melt easily** (plastic) contribute to rapid fire propagation (F070). Materials such as **vinyl** for window framing, **stucco** for exterior construction, and **tile** for roofing have demonstrated **higher survival rates** compared to their counterparts (**metal, wood, masonry, composite, metal, shake, shingle**) (F059). Materials with **low thermal conductivity**, such as **aerogel** (F004) and **expanded perlite** (F071), can slow heat transfer but may have limitations in other properties. Fire safety and wind-borne debris impact resistance are increased with **brick construction**. Bricks do not emit toxins to the environment when exposed to fire. Bricks provide thermal mass, reducing energy requirements by slowing the transfer of heat and cold (F001) The type of insulation, its thickness, and its location within the building envelope significantly impacts fire performance, e.g. **rockwool** is a non-combustible mineral wool which has high thermal resistance, while **extruded polystyrene**, despite being used for its durability, has poor thermal resistance (F068, F070, F072). Grenfell Inquiry Phase 1 Report: “The principal reason why the flames spread so rapidly up, down and around the building was the presence of the **aluminium composite material (ACM) rainscreen panels with polyethylene cores**, which acted as a source of fuel. The

Category	Key sensitivities to wildfires
	principal mechanism for the spread of the fire horizontally and downwards was the **melting and dripping of burning polyethylene from the crown** and from the spandrel and column panels, which ignited fires lower down the building. The presence **of polyisocyanurate (PIR) and phenolic foam insulation boards** behind the ACM panels, and perhaps components of the window surrounds, contributed to the rate and extent of vertical flame spread."
Building design	Well-known sensitivities of building design to wildfires comprise **roofing, dormers, gutters, eaves and vents, sidings, windows and glazing, decks, porches and patios, fences, and mulch and debris** (D97, 93, 90). More than 60% of the fires in dwellings (USA) were directly associated with the propagation of firebrands. Around 80% began in **roofs, doors and windows**. More than 90% of the houses built with **masonry walls and wooden roofs and floors** were much more susceptible to fire than the **reinforced concrete structures** (D97). **Subfloor systems** of buildings that are elevated on stumps above the ground are vulnerable (D93). **Open windows and vents** are reported as to be two of the most common entrance points of firebrands in Mediterranean Europe (D93). **A complex roof design**, e.g. with intersections between roof and walls (e.g. a **dormer**) or geometric features such as valleys or gullies increases roof vulnerability to fire as it provides the accumulation of firebrands or even dead vegetation which may be ignited by firebrands (D97).
Building age	**Historic buildings** can be more sensitive to fire and fire damage in particular buildings that have a high amount of combustible materials. (A102) This can include "surface treatments, decorative paint and interior details" that "In addition to acting as a fuel source, are extremely vulnerable to damage from fire and smoke as well as from fire suppression media, such as water or foam" (A32). **Undivided roof voids** present in **historic building** can allow fire to spread rapidly (A101). Damage from fires in **historic buildings** include: "Fire causes material loss and deformation of **cultural heritage assets** and may also increase the probability of cracking or splitting in

Category	Key sensitivities to wildfires
	built structures" (A42). "Heat damage, fracturing and loss of stonework to monuments and buildings and loss of organic construction materials from fire are particular risks here" (A102). A study on wildfires in California concluded "Although the notion of building back better forms a hallmark of disaster recovery, from global frameworks to individual jurisdictions, in reality, recovery often prioritizes rebuilding and de-emphasizes risk" (A83) suggesting that **modern houses are just as susceptible to wildfire damage as older houses.** Risk of loss of housing to wildfire is strongly **dependent on location and arrangement of buildings as opposed to age** (A83).

A.1.2.4 Pests

Table 17 Key sensitivities of building categories to pests

Category	Key sensitivities to pests
Building type	**Modern, well-insulated homes are sensitive to dust mite infestations** due to their warm and potentially humid indoor environments (T88). **New-build homes and bungalows** are especially prone to overheating during the hot UK summers, making them more sensitive to insect infestations (T150). **Heritage buildings are sensitive to various pests** due to changes in biological growth patterns resulting from climate change, particularly warmer temperatures and wetter winters (T36, T74, T156, T157, T162, T166, T167). This is due to the materials used in construction such as timber. For example, termites have been discovered at two **National Trust properties** in Devon with timber frames. The furniture beetle is also frequently recorded in **wooden heritage properties**, including **churches and museums**, where they leave holes in **wood structures** (T156, T167). **Heritage buildings are currently sensitive**, with the most frequent insect pests found in English Heritage properties including booklice, silverfish, woodlice, plaster beetle, woolly bear larvae, carpet beetle, and the webbing clothes moth (this doesn't correlate to damage by the pests). (T156).
Building fabric	High wind speeds can drive rain into the building envelope, increasing moisture levels in walls, roofs, and other components. This creates a conducive environment for the proliferation

Category	Key sensitivities to pests
	of insects (F076, F080, F081). Extreme wind can cause physical damage to the building envelope, creating openings for water ingress and insect entry (F077). **Different woods vary in their relative resistance to termites**. Some species typically considered resistant are bald cypress, eastern red cedar, chestnut, Arizona cypress, black locust, redwood, Osage orange, black walnut, and Pacific yew. It should be noted that even the most resistant woods cannot be considered termite barriers. Termites can tube over resistant wood and attack susceptible wood (F075). **CLT** is a **prefabricated engineered wood panel** that consists of crosswise stacked boards glued together using adhesive mostly fabricated from less-durable softwood lumber, which is **susceptible to the infestation** of insects and termites, especially when used in warm and humid regions (F076). **Timber** is threatened by insects such as carpenter ants (Camponotus spp.), termites (Epifamily: Termitoidae), bark beetles (subfamily Scolytinae), longhorn beetles (Family: Cerambycidae), weevils (Superfamily: Curculionoidea), and powderpost beetles (superfamily Bostrichoidea). The **deathwatch beetle** (Xestobium rufovillosum) is especially well-known in historic structures as it **prefers aged oak timber rather than softwood** (F082). **Powderpost beetle** (Luctus bunneus) may find future conditions in the UK more favourable and attackh **sapwoods** used in property repairs. Additionally **subterranean termite** (Reticulitermes flavipes) is potentially an accidental import to the UK and may become more common given current temperatures are suitable for survival in well-drained loamy soils, and future climates would allow a presence in the north of England.
Building design	**Evidence gap:** Lack of evidence that directly linked building design to the occurrence and mortality of pests. Literature predominantly identifies relationship between pests and age, fabric, and type.
Building age	The change in climate is influencing a change in pest patterns. Increased temperatures can lead to the spread of insects to previously inhospitable areas. An increased temperature could also increase the activity and growth cycle rate of pests which would increase damage levels (A3, A53, A54, A79).

Category	Key sensitivities to pests
	Historic buildings are more sensitive to pests due to a large presence of wood in their building fabric. Wood seems to be the preferred habitat for pests (some also attack books and other historic/ museum items) (A42, A43, A94). **Large historic buildings** are often difficult to seal and remain sensitive to infestations. They often also have a resident population of pests within the building: this can be underneath floorboards, but also unused chimneys, shafts or the attic. (A92) **Historic buildings** are often part of park-like landscapes with some dead trees. Sensitivity to an infestation due to this outdoor component is higher than in museums within cities. (A92) The main pests that are of concern to **historic buildings are**: longhorn beetle, death watch beetle, termites, furniture beetle, brown carpet beetle and new pests from other regions. (A42, A43, A53, A79, A92, A98, A99, A102)

Appendix 2 – Data used in this study

A.2.0 Overview

This section outlines the key details of the hazard datasets collected as key inputs into the exposure analysis and mapping. A table is provided below, sharing key details of the datasets such as unit of measurement, source, spatial resolution and coverage, timeframes, climate scenarios, and percentiles used where relevant.

The two types of climate scenarios used in the analysis are **Representative Concentration Pathways (RCPs)** and **Global Warming Levels (GWLs)**:

- GWLs represent potential increases in the global average temperature by the end of this century. 2°C and 4°C GWLs have been used in this analysis for the analysis of WDR and pests. These GWLs represent scenarios in which average global temperatures are kept below a 2°C and 4°C increase above pre-industrial levels, by 2100. The Climate Change Committee (The CCC) communicates these two levels as a reasonable reflection of possible future outcomes, recognising that they are dependent on the success of current global efforts to reduce greenhouse gas emissions and mitigate climate change (The CCC, 2020).
- RCPs are a type of climate scenario developed for the IPCC's Fifth Assessment Report (AR5). They are inputs to climate models that represent the radiative forcing level that could be reached by 2100, compared to pre-industrial levels, without consideration of socio-economic factors. Radiative forcing is the difference between the energy the Earth receives from the sun and the energy it radiates back into space, influenced by changes in the atmosphere. A positive radiative forcing indicates that radiation is trapped in the Earth's atmosphere, warming that planet. RCPs 4.5 and 8.5 have been used in this analysis where available (for wildfires), and in some cases only RCP8.5 was available and therefore used alone (for subsidence and extreme wind). RCP4.5 is a moderate climate scenario, representing a 4.5 watts per metre squared (W/m^2) increase in radiative forcing by 2100, since pre-industrial levels, which equates to a GWL of approximately 2.4°C, while RCP8.5 is a comparatively

high greenhouse gas emissions scenario (Van Vuuren, 2011) representing a radiative forcing of 8.5W/m² by 2100, equating to a GWL of approximately 4.3°C.

For simplicity in the interactive map, where different percentiles in the model outputs are available i.e. there is a choice of which individual climate model outputs to use from an ensemble, the outcomes from the *median* climate model have been used. This ensures consistency in the model selection between the hazards.

A.2.1 Hazard data

Table 18 Hazard data details

Hazard	Dataset name	Unit of measurement	Source	Data file format	Spatial factors		Timeframes			Climate scenarios	Percentiles
					Resolution	Coverage	Interval	Historical data	Projections		
Extreme wind	Wind speed gust maximum	Metres per second	UKCP18 / Centre for Environmental Data Analysis (CEDA) Archive	NetCDF	2.2km aggregated to 5km grid	UK wide	Annual	1981-2000	2021-2040 2061-2080	RCP8.5[15]	n/a
Wind-driven rain	Annual index of wind driven rain	Annual index of wind driven rain (sum of all wind-driven rain spells in each year)	UKCP18 / Met Office Climate Data Portal	GeoJSON	2.2km aggregated to 5km grid	UK wide	Annual	1981-2000	Use of global warming levels (GWLs)	2°C and 4°C GWLs	Median of ensemble
Subsidence	GeoClimate	Hazard rating (3 classes: 1. Improbable 2. Possible 3. Probable)	Previous BGS work	GIS polygon data (ESRI)	2km grid	UK wide	11-year intervals	None (only available with license)	2025-2035 2065-2075	RCP8.5[15]	n/a

[15] Equivalent to 4.3°C of warming by 2100 compared to preindustrial levels

Hazard	Dataset name	Unit of measurement	Source	Data file format	Spatial factors		Timeframes			Climate scenarios	Percentiles
					Resolution	Coverage	Interval	Historical data	Projections		
Wildfires	Met Office Fire Danger	Number of days per year to experience 'very high' fire danger	UK Climate Risk Indicators	GeoJSON	12km grid	UK wide	30-year intervals	1981-2010	2021-2050 2061-2090	RCP4.5[16] RCP8.5[15]	Median of all members
Pests	Bias corrected mean air temperature (Tmean)	Degrees Celsius	Bristol University	NetCDF	12km grid	UK wide	Daily	Historical Tmean data not used.[17]	Use of global warming levels (GWLs)	2°C and 4°C GWLs	Median of ensemble

Table 19 Pest observations data details

Species		Source
Latin species name	English species name	
Hylotrupes bajulus	House longhorn beetle	Hylotrupes bajulus : Old House Borer | NBN Atlas [H010]

[16] Equivalent to 2.4°C of warming by 2100 compared to preindustrial levels
[17] Instead, all historical, observed records of each pest species used as point-data, sourced from What's Eating Your Collection [H008] and the NBN Atlas [H009].

Species		Source
Latin species name	English species name	
Xestobium rufovillosum	Death watch beetle	Xestobium rufovillosum : Death-watch Beetle | NBN Atlas [H011]
Oligomerus ptilinoides	Bamboo powder post beetle	What's Eating Your Collection? [H008]
Attagenus smirnovi	Brown carpet beetle	What's Eating Your Collection? [H008]
Stegobium paniceum	Biscuit beetle	What's Eating Your Collection? [H008]
Anobium punctatum	Common furniture beetle	Anobium punctatum : Common Furniture Beetle | NBN Atlas [H012]
Coptotermes formosanus	Formosan subterranean termite	What's Eating Your Collection? [H008]

For some of the climate-related hazards, additional data has been used to supplement the hazard data, to build a fuller picture of exposure to the hazard and has therefore been integrated into the exposure analysis. Details of these additional inputs, and the reasoning and methodology of combining them with the hazard data, are provided per hazard in the following Appendix ().

A.2.2 Building data

A.2.2.0 Lower Layer Super Output Area (LSOA) level data

LSOA (Lower Layer Super Output Area) level data, provided by the Office of National Statistics, is used to provide building attributes for the analysis of subsidence *only*. The LSOA level is a geographic area used in England and Wales for reporting small area statistics. They have an average population of between 1000 and 3000 people, or between 400 and 1200 households. The LSOA polygons cover every house, however the LSOA data assimilates these data to provide generic statistics per area. This is used in the analysis of subsidence only as it is embedded within the **Shrink Swell Building Susceptibility Score** provided by BGS (detailed below in Section A.3.3).

A.2.2.1 Local authority search function

In the interactive map, there is a Local Authority search function, which enables users to zoom to key areas of interest and can be useful to refer to a specific location or building. This is an initial function to enable searchability for the user.

A.2.2.2 National Buildings Database (NBD)

In future improvements to the interactive map, the National Buildings Database (NBD) will be used to provide detailed buildings data within the map. The NBD is currently being developed by DESNZ and UCL and is a detailed inventory of all buildings across Great Britain. With support from UCL, the NDB was considered throughout the project, particularly during the collection of hazard data and the development of exposure scores for each of the hazards to ensure alignment with the NBD data and enable the NBD data to be embedded within the interactive map once it is developed.

Appendix 3 – Analysis of climate-related hazards

This section provides details of the methodology for analysing each hazard, in terms of identifying an appropriate approach for determining exposure scores, and how these scores were calculated to produce information that can be meaningfully mapped, to show the UK-wide exposure to each hazard. It also provides further details of key inputs into the analysis of each hazard.

A.3.0 Extreme wind

A.3.0.0 Identification

The extreme wind exposure score is determined using the hazard data only, which is the UKCP18 wind speed gust maximum data. The score is expressed on a scale of 0-5, with increasing value corresponding with higher wind gust speeds and therefore greater exposure to extreme wind.

The exposure score is based on the percentile at which the wind gust speed falls within the distribution of values for all grid cells across the UK by 2080. Percentile values are scaled from the range 0-100 to the range 0-5 to provide scores on a scale that aligns with exposure scores of the other hazards, defined in Table .

Table 20 Extreme wind exposure score definitions

Score	Rating definition
0.1 - 1	Lowest quintile of wind gust speeds by 2080 (amongst all 5km grid cells across UK)
1.1 - 2	Second quintile of wind gust speeds by 2080 (amongst all 5km grid cells across UK)
2.1 - 3	Third quintile of wind gust speeds by 2080 (amongst all 5km grid cells across UK)
3.1 - 4	Forth quintile of wind gust speeds by 2080 (amongst all 5km grid cells across UK)
4.1 - 5	Highest quintile of wind gust speeds by 2080 (amongst all 5km grid cells across UK)

A.3.0.1 Calculation

The exposure scores on a scale of 0-5 were calculated by taking the maximum wind gust speed over the whole dataset, and then dividing the number 5 by this maximum. This produced the percentile values, as described above, distributing the wind speed values as scores out of 5.

This aligns with the calculation of the fire danger scores for wildfire exposure and the exposure scores for wind driven rain.

The scoring was calculated and applied directly to the grid cells in GIS per year, and the maximum was found for the periods of 1980-2000, 2020-2040, 2060-2080, to represent the most extreme wind loads that have occurred and are projected to occur across these timeframes.

The assumptions and limitations associated with this methodology for extreme wind are outlined in Section 4.1.1.

A.3.1 Wind driven rain

A.3.1.0 Identification

The wind driven rain (WDR) exposure score is determined using the hazard data only, which is the Met Office's annual index of WDR data. The score is on a scale of 0-5, with increasing value corresponding with a higher volume of rain blown from a given direction and therefore greater exposure to spells of WDR. The exposure scores are assigned per wind direction to provide exposure information for different wall orientations.

Both the 2°C and 4°C Global Warming Levels (GWLs) are used in the projections of WDR, (see Section A.2.1 for an introduction to GWLs), aligning with the GWLs used for the pest exposure analysis. As the GWLs are embedded within the hazard data, no model selection process was necessary for this hazard.

The exposure score is based on the percentile at which the volume of WDR sits within the distribution of values for all grid cells across the UK at the GWL of 4°C. Percentile values are scaled from the range 0-100 to the range 0-5 to provide scores on a scale that align with exposure scores of the other hazards, defined in Table 15.

Table 21 Wind driven rain exposure score definitions

Score	Rating definition
0.1 - 1	Lowest quintile of wind driven rain in a 4°C world (amongst all 5km grid cells across UK)
1.1 - 2	Second quintile of wind driven rain in a 4°C world (amongst all 5km grid cells across UK)
2.1 - 3	Third quintile of wind driven rain in a 4°C world (amongst all 5km grid cells across UK)

Score	Rating definition
3.1 - 4	Forth quintile of wind driven rain in a 4°C world (amongst all 5km grid cells across UK)
4.1 - 5	Highest quintile of wind driven rain in a 4°C world (amongst all 5km grid cells across UK)

A.3.1.1 Calculation

The exposure scores on a scale of 0-5 were calculated by identifying the maximum WDR over the whole dataset, across all wind directions and climate models, and then dividing the number 5 by this maximum. This produced the percentile values, as described above, distributing the WDR values as scores out of 5. The scores were calculated using the maximum WDR across all wind directions to allow for direct comparison between them. This method of calculating the scores aligns with that of the fire danger scores for wildfire exposure and the exposure scores for extreme wind.

The scoring was calculated and applied directly to the grid cells in GIS for each year relevant to the GWLs that were analysed, both 2°C and 4°C.

The assumptions and limitations associated with this methodology for WDR are outlined in Section 4.1.2.

A.3.2 Subsidence – clay shrink swell

A.3.2.0 Identification

The clay shrink-swell subsidence sensitivity score is calculated by combining two subsidiary scores; the **GeoClimate OPEN score**, which provides an indication of hazard exposure, and the **SSBSS (Shrink Swell Building Susceptibility Score)** score, which provides an indication of hazard sensitivity.

GeoClimate OPEN provides exposure information on the potential for clay shrink-swell to occur at a given location, during a given future time period, based on a combination of geological, hydrological and climate projection data. GeoClimate OPEN, summarised in Table 3, is a 1:4000,000 scale product, consisting of 2km grid squares, The outputs are provided for time period envelopes, centred on 2030 (11-year window 2025 to 2035) and 2070 (11 year window 2065 to 2075), with 1 average dataset provided for each time period. The dataset is based on a generalisation of the GeoClimate Premium dataset and uses the median average outcome for the RCP8.5, combined with the geological susceptibility. The outputs use the worst-case shrink-swell score for each 2km grid cell. It can be viewed here: GeoIndex - British Geological Survey [H013]. Information on methodology, such as input datasets and further technical information can be found in the BGS User Guide [H014].

Table below shows the GeoClimate Open data classifications and their definitions.

Table 22 GeoClimate Open data classifications

GeoClimate OPEN Class	Associated susceptibility text (legend text)
Improbable	It is improbable that climate change will affect clay shrink-swell susceptibility and change the likelihood of ground movement, which causes subsidence.
Possible	It is possible that climate change will affect clay shrink-swell susceptibility and change the likelihood of ground movement, which causes subsidence.
Probable	It is probable that climate change will affect clay shrink-swell susceptibility and change the likelihood of ground movement, which causes subsidence.
Unavailable	Input datasets unavailable.

The **SSBSS (Shrink Swell Building Susceptibility Score)** score is calculated based on BGS expert knowledge and experience and reflects the controlling factors that influence the sensitivity of a building to clay shrink-swell subsidence. The input dataset is the LSOA level dataset (described in Section A.2.3.1). This input provides generic statistics per LSOA area, on the following components.

Age of property

Due to changes in foundation design and building regulations, the age of a property provides an indication of the foundation depth likely to be associated with a building. This information is derived from the LSOA results where counts of property age within each LSOA includes a breakdown by age into 13 property period categories. These are grouped into 4 categories based on when building regulations were updated.

Building Type

The type of building (e.g. bungalow, terrace house) has an influence on the potential extent of structural damage, should movement occur. Damage to a structure is possible when as little as 3% volume expansion takes place, and especially when these movements are unevenly distributed beneath a foundation or property. This information is derived from the LSOA results, where counts of property type within the LSOA includes a breakdown by type into 28 categories, including versions of bungalow, terraced, flat/maisonette, semi-detached and detached. These are grouped into 5 categories.

Number of storeys

The height of a building has an influence on the resultant structural damage should movement occur, especially when these movements are unevenly distributed beneath a foundation or property. This information is derived from the LSOA results, where counts on property type includes a breakdown by bungalow, terraced, flat/maisonette, semi-detached and detached, and the number of stories is inferred from the dataset. These are grouped into 3 categories.

Table 23 Descriptions and possible values for the building polygon attributes

Name	Description	Range of values
Age	A score (1-10) for the area indicating the subsidence susceptibility due to the age of a buildings and hence foundation depths.	1 to 10 Used as an indication of foundation conditions. 10 indicating buildings with poorest foundations and hence higher susceptibility to shrink swell motions and 1 indicating buildings with the most resistant foundations
Storey	A score (1-10) for the area indicating the subsidence	1 to 10 10 indicating buildings with least number of stories therefore likely to

Name	Description	Range of values
	susceptibility due to the number of storeys in a building	have poorer foundations and 1 indicating the highest buildings which are therefore likely to have better designed foundations.
Type	A score (1-10) for the area indicating the subsidence susceptibility due to the building type (detached, bungalow etc.).	1 to 10 10 indicating the buildings with least support from adjacent buildings and 1 indicating buildings with the most support from adjacent buildings.

A.3.2.1 Calculation

To create an area sensitivity score output, the datasets described above are combined. The LSOA polygons, with associated SSBSS values, were intersected with the GeoClimate OPEN 2km grid and each SSBSS value from the intersect was considered equally. The median value of these SSBSS scores provides the final area sensitivity score per grid cell.

To summarise, the rating values were calculated using the formula below:

Area Sensitivity Score = **GeoClimate OPEN score** + **SSBSS**

The classification for this new output is provided in Table below.

Table 24 Matrix grid showing the classification of the Area Sensitivity Score

SSBSS: LSOA Building attributes	GeoClimate OPEN score: Improbable	GeoClimate OPEN score: Possible	GeoClimate OPEN score: Probable
No significant building attribute	No increase in sensitivity to clay shrink-swell subsidence	A small increase in sensitivity to clay shrink-swell subsidence	A small increase in sensitivity to clay shrink-swell subsidence

SSBSS: LSOA Building attributes	GeoClimate OPEN score: Improbable	GeoClimate OPEN score: Possible	GeoClimate OPEN score: Probable
1 significant building attribute	No increase in sensitivity to clay shrink-swell subsidence	A small increase in sensitivity to clay shrink-swell subsidence	A medium increase in sensitivity to clay shrink-swell subsidence
2 significant building attributes (age and storey)	No increase in sensitivity to clay shrink-swell subsidence	A small increase in sensitivity to clay shrink-swell subsidence	A large increase in sensitivity to clay shrink-swell subsidence
2 significant building attributes (age and type)	No increase in sensitivity to clay shrink-swell subsidence	A medium increase in sensitivity to clay shrink-swell subsidence	A large increase in sensitivity to clay shrink-swell subsidence
3 significant building attributes	No increase in sensitivity to clay shrink-swell subsidence	A large increase in sensitivity to clay shrink-swell subsidence	A large increase in sensitivity to clay shrink-swell subsidence

The area sensitivity data outputs are attributed with the following information:

Table 25 Attribute table field descriptions and possible values for the 2km grid squares within the output dataset

FIELD NAME	DESCRIPTION	RANGE OF VALUES
OID	An automatically generated sequential unique identifier	0 - 61281
GCCLASS	GeoClimate OPEN classification	Improbable, Possible, Probable
IGCCLASS	Numeric value for the GeoClimate OPEN classification	0-9

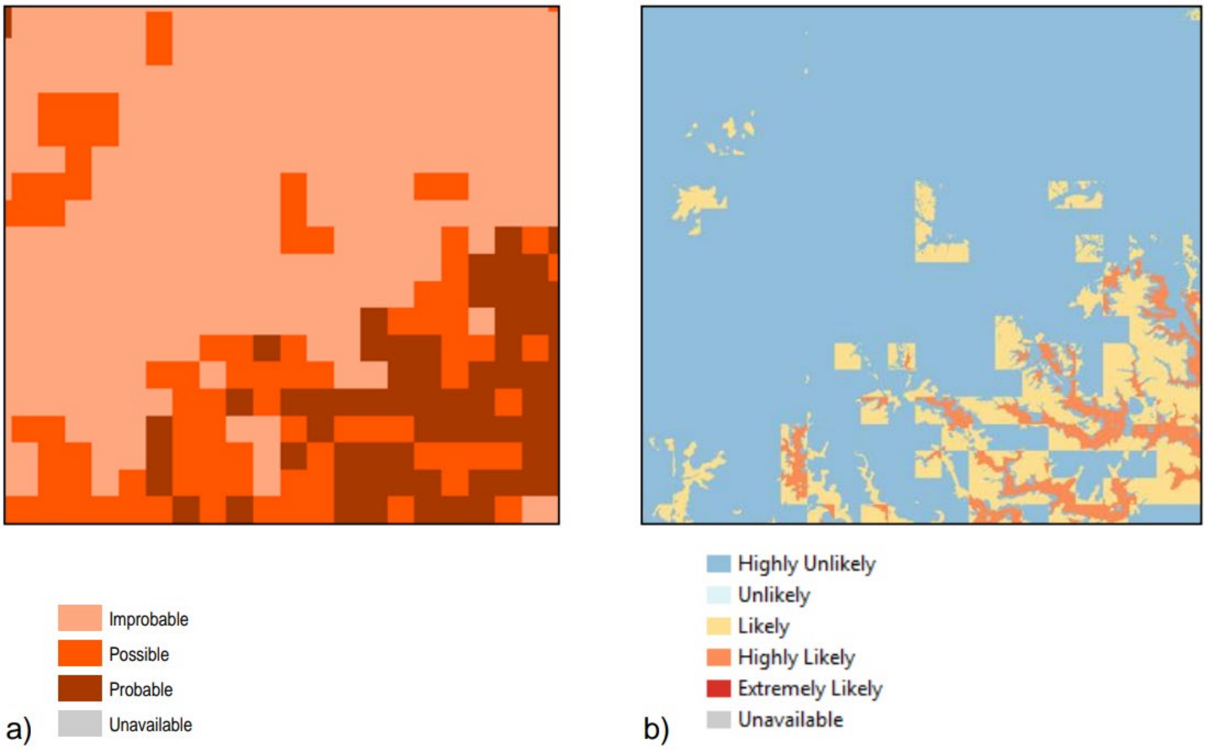
FIELD NAME	DESCRIPTION	RANGE OF VALUES
SSBSSCOUNT	Number of LSOA polygons within the 2km grid square	0-61
SSBSSLIST	SSBSS scores for each of the LSOA polygons within the 2 km grid square	List of up to 61 SSBSS scores, from 0 -
RATINGLIST	All calculated sensitivity scores for each of the LSOA polygons within the 2 km grid square. Calculated using the SSBSSLIST and IGCCLASS values	List of all sensitivity score values for all LSOA polygons within the 2 km grid square, separated by commas.
RMIN	The minimum sensitivity score for all LSOA polygons within the 2 km grid square	-999[18] to 180
RMAX	The maximum sensitivity score for all LSOA polygons within the 2 km grid square	-999 to 180
RMED	The median sensitivity score for all LSOA polygons within the 2 km grid square	-999 to 180
RMEAN	The mean sensitivity score for all LSOA polygons within the 2 km grid square	-999 to 180
RSKEW	Pearson's skewness	-999 to 7.21.

[18] -999 represents null values

FIELD NAME	DESCRIPTION	RANGE OF VALUES
		If the mean is greater than the median, the distribution is positively skewed. If the mean is less than the median, the distribution is negatively skewed.
RCLASS	Area Sensitivity Score classified from the RMED	No impact, small increase, medium increase, high increase
RLEGEND	Expanded text for the Area Sensitivity Score classified from the RMED	No increase in sensitivity to clay shrink-swell subsidence, Small increase in sensitivity to clay shrink-swell subsidence, Medium increase in sensitivity to clay shrink-swell subsidence, High increase in sensitivity to clay shrink-swell subsidence, No Data
VERSION	Name and Version Number of dataset	GeoClimateUKCP18_ShrinkSwell_2030_Average_CSNOW_BETA

The assumptions and limitations associated with this methodology for subsidence are outlined in Section 4.1.3. Regarding the final limitation for this methodology, GeoClimate clay shrink-swell is available in two versions: GeoClimate Open which is a freely available overview dataset and GeoClimate Premium which is a licensed (paid-for) higher resolution and more detailed dataset. This means this study used a lower resolution of data. Figure 13 below demonstrates the difference in resolution between GeoClimate Premium and Open, for an area in the south-east of Great Britain.

Figure 12 Comparison of GeoClimate a) Open and b) Premium



A.3.3 Wildfires

A.3.3.0 Identification

The wildfire exposure score is calculated by combining three subsidiary scores: the **rural/urban score**; the **land cover score**, and the **fire danger score**. The score for each component of overall exposure is expressed on a scale of 0-5, with increasing value corresponding with greater exposure to wildfire. The next section (A.3.4.2) provides details of how the subsidiary scores were combined.

The **rural/urban score** is determined qualitatively based on expert judgement of the extent of the rural/urban fringe in different rural/urban land categories and reflects the degree of connectivity between built-up areas to flammable (vegetated) landscapes. Contact between urban areas and the vegetated landscape at the wildland-urban interface (WUI) allows wildfires to spread from vegetated land into the built-up environment, thus influencing exposure of buildings to wildfire (e.g., Chen et al., 2024; Caton et al., 2016; Moritz et al., 2022). The rural/urban data that was used to assign scores to and layer with the other components to produce the final mapped output for wildfires, were the 2011 classification for England and Wales (2011 Rural Urban Classification - GOV.UK), the 2015 data for Northern Ireland (Urban - Rural Classification | Northern Ireland Statistics and Research Agency), and 2020 data for Scotland (Urban Rural Classification - Scotland - data.gov.uk). The most up to date version of the regional classifications were used where possible, but higher resolution data was prioritised to ensure greater detail within the map. Table presents the definitions, and examples, of the rural/urban scores.

Table 26 **Rural/urban** score definitions and examples

Score	Rating definition	Example
1	High density of buildings, but with extremely low ratio of fringe to built-up	Major urban conurbation
2	Intermediate density of buildings, but with low ratio of fringe to built-up	Small towns
3	Low-intermediate density of buildings, with intermediate ratio of fringe to built-up	Rural town and fringe
4	Low density of buildings, with high ratio of fringe to built-up	Remote rural town
5	Intermediate density of buildings, with high ratio of fringe to built-up	Rural village

The **land cover score** is determined qualitatively based on expert judgement of the propensity for extreme fire behaviour to occur on different land covers, given the fuel loads, fuel density and fuel structure. The criteria applied during scoring are provided below along with examples of the land cover types receiving each score. Spread of wildfire from rural land built-up areas across the WUI is particularly likely if there are dense fuel stocks on rural land. Dense fuel stocks promote intense burning, more extreme fire behaviour, higher pre-heating of peri-urban fuels, and greater production of embers which all elevate the likelihood of wildfires spreading across the WUI (e.g., Chen et al., 2024; Caton et al., 2016; Moritz et al., 2022). The data used was the UK Centre for Ecology & Hydrology land cover maps (UKCEH Land Cover Maps | UK Centre for Ecology & Hydrology) at the 25m resolution, and the processing time for the 10m resolution was extensive and therefore inefficient to include. Table presents the definitions, and examples, of the land cover scores.

Table 27 **Land cover** score definitions and examples

Score	Rating definition	Example
0	Assumes negligible fuel load	Rock
1	Limited and disconnected fuels, e.g. due to manmade surfaces	Suburban
2	Intermediate density low-lying fuel stocks	Grassland
3	Dense low-lying fuel stocks	Arable
4	High fuel stocks without densest fuel structure	Shrubland, Deciduous Woodland
5	High fuel stocks with densest fuel structure favouring extreme fire behaviour	Coniferous Woodland

The **fire danger score** is based on the annual number of days projected to experience very high fire danger under future climate change. The 'very high' fire danger threshold for the UK is calculated by the Met Office (Kitchen, 2006; de Jong et al., 2016; Perry et al., 2021), based on the distribution of values of the fire weather index (FWI; high threshold = 17.35). 60% of UK fires occur when FWI exceeds the threshold value of 17.35 (Kitchen, 2006; de Jong et al., 2016; Perry et al., 2021). The Met Office provides projections of the annual number of days (*n*) with very high fire weather through 2100 under a high emissions scenario (RCP8.5; Perry et al., 2021;Climate Risk Indicators). The fire danger score is based on the percentile at which each output area's *n* score falls within the distribution of values for all output areas by 2090. Percentile values are scaled from the range 0-100 to the range 0-5 to ensure compatibility with the scores landscape factors score. Table presents the definitions of the fire danger scores.

Table 28 **Fire danger** score definitions

Score	Rating definition
0.1 - 1	Lowest quintile of fire danger days by 2090 (amongst all OAs)
1.1 - 2	Second quintile of fire danger days by 2090 (amongst all OAs)
2.1 - 3	Third quintile of fire danger days by 2090 (amongst all OAs)
3.1 - 4	Fourth quintile of fire danger days by 2090 (amongst all OAs)
4.1 - 5	Highest quintile of fire danger days by 2090 (amongst all OAs)

A.3.3.1 Calculation

The scores **rural/urban score**, **land cover score**, and **fire danger score** are combined using the following equations:

(Eq. 1) **Landscape_factors_score** = (**Rural_urban_score** + **Land_cover_score**) / 2

(Eq. 2) **Wildfire_exposure_score** = (**Landscape_factors_score** + **Fire_danger_score**) / 2

The land cover score and rural/urban score are combined into an overall landscape factors score through averaging (equation 1) and rounded to the nearest whole number, as shown in Figure 14 below. Resulting values can fall within the range of 0 to 5. Any area with a land cover score of 0 is assigned a 0 for the landscape factors score as this implies an area has negligible fuel load, and therefore is not exposed to potential wildfire occurrence regardless of the WUI.

Figure 13 Matrix to determine landscape factors scores (equation 1)

Landscape factors scores		Land cover					
		0	**1**	**2**	**3**	**4**	**5**
Rural urban	**1**	0	1	2	2	3	3
	2	0	2	2	3	3	4
	3	0	2	3	3	4	4
	4	0	3	3	4	4	5
	5	0	3	4	4	5	5

The overall wildfire exposure score is then calculated by averaging the landscape factors score and the fire danger score (equation 2) and rounding to the nearest decimal place. Resulting values can fall within the range of 0 to 5 and scores are registered at one decimal precision within the range 0-5. This is shown in Figure 15 below, for every 0.5 increment as an example (not all 0.1 increments are shown).

Figure 14 Matrix to determine overall wildfire exposure scores (equation 2)

Wildfire exposure scores		Landscape factors					
		0	1	2	3	4	5
Fire danger	0	0.0	0.5	1.0	1.5	2.0	2.5
	0.5	0.3	0.8	1.3	1.8	2.3	2.8
	1	0.5	1.0	1.5	2.0	2.5	3.0
	1.5	0.8	1.3	1.8	2.3	2.8	3.3
	2	1.0	1.5	2.0	2.5	3.0	3.5
	2.5	1.3	1.8	2.3	2.8	3.3	3.8
	3	1.5	2.0	2.5	3.0	3.5	4.0
	3.5	1.8	2.3	2.8	3.3	3.8	4.3
	4	2.0	2.5	3.0	3.5	4.0	4.5
	4.5	2.3	2.8	3.3	3.8	4.3	4.8
	5	2.5	3.0	3.5	4.0	4.5	5.0

Within the overall wildfire exposure score, the rural/urban score, land cover score, and fire danger score have weightings of 25%, 25% and 50%, respectively. This leads to a 50:50 weighting between landscape factor score and fire danger score.

The assumptions and limitations associated with this methodology for wildfire exposure are outlined in Section 4.1.4.

A.3.4 Pests

A.3.4.0 Identification

The exposure scores for pests were determined using two key factors a. mean air temperature data (outlined in Table 6) and b. information about temperature thresholds for the development of specific pest species (Table). For one of the species, information on GDD was also used to provide an indication of the exposure of buildings to that pest. The factors used to develop the exposure scores per species were dependent on the information available and are detailed further below. The analysis was conducted at the 2°C and 4°C GWLs, aligning with those used for the WDR exposure analysis.

Pest species

The pests included in the analysis were selected through expert judgement. They are deemed by experts to be a potential problem in the future for the UK building stock due to changing climate conditions and rising average temperatures, through factors such as potential pest migration around and to the UK, enhanced development of species e.g. through potentially higher reproductive rates, or changes to the rates of pest mortality. The pests are: *Hylotrupes bajulus* (house longhorn beetle); *Xestobium rufovillosum* (death watch beetle); *Oligomerus ptilinoides* (bamboo powder post beetle); *Attagenus smirnovi* (brown carpet beetle); *Stegobium paniceum* (biscuit beetle); *Anobium punctatum* (common furniture beetle); and *Coptotermes formosanus* (Formosan subterranean termite). Some other species were identified for the analysis but have been excluded due to a lack of available information on temperature thresholds for development and GDD, including but not limited to: *Lyctus brunneus* (powder post beetle); *Reticulitermes flavipes* (eastern subterranean termite); and *Zootermopsis nevadensis* (dampwood termite).

Temperature thresholds

The table below shows the temperature thresholds identified for each species and what each threshold implies for pest development. The thresholds provide an indication of whether a location is projected to experience a temperature that can be associated with no, slow, or optimal development for a species at any stage of the life cycle, or temperatures that are high enough to potentially lead to pest mortality. This information was found through desk-research of academic literature and supplemented with expert judgement.

Table 29 Pest species and temperature thresholds

Latin species name	English species name	Temperature threshold	Threshold meaning	Comments from literature
Hylotrupes bajulus	House longhorn beetle	<20°C	Slow development rate	n/a
		20-30°C	Optimal temperature	20-30°C is optimal (Sibilla et al., 2016) 25°C larvae are particularly active and develop most efficiently (Berzolla et al., 2011)
		>30°C	Slow development rate	n/a
		<10°C	Possibly dormant	<10°C development of larvae notably slowed and may enter

Latin species name	English species name	Temperature threshold	Threshold meaning	Comments from literature
Xestobium rufovillosum	Death watch beetle			dormancy (Karbowska-Berent et al., 2020)
		10-20°C	Slow development rate	n/a
		20-30°C	Optimal temperature	20-30°C / 25°C for optimal growth (Karbowska-Berent et al., 2020)
		>30°C	Increased mortality rate	>30°C increased larvae mortality rate (Martinson, 2020)
Oligomerus ptilinoides	Bamboo powder post beetle	<10°C	Slow larval development rate	<10°C is a slowdown in larval development (Klinc and Pohleven, 2017)
		10-20°C	Reduced development rate	n/a
		20-30°C	Optimal temperature	20-30°C increased feeding activity and development rates (Klinc and Pohleven, 2017)
		>30°C	Slow development rate	n/a
Attagenus smirnovi	Brown carpet beetle	<19°C	Slow development rate	n/a
		19-29°C	Optimal temperature	Optimal conditions at 24°C (Brimblecombe, 2024)
		29-34°C	Slow development rate	24°C is optimal, and 34°C is the upper limit for larvae development (Brimblecombe, 2024)
		>34°C	Upper limit for larval survival	34°C is the upper limit for larvae development (Brimblecombe, 2024)
Stegobium paniceum	Biscuit beetle	490 degree days above baseline of 15°C *For example, a day where the mean temperature is 16°C equates to 1 degree day and a day with a mean temperature of*	Species development	490 degree-days above 15°C threshold for 1 lifecycle (Brimblecombe and Lankester, 2012)

Latin species name	English species name	Temperature threshold	Threshold meaning	Comments from literature
		20°C equates to 5 degree days.		
Anobium punctatum	Common furniture beetle	>25°C	Flight occurs increasing chance of spreading infestation	Does not readily fly below 25°C (Brimblecombe and Lankester, 2012)
		<25°C	No flight, reducing chance of spreading infestation	
Coptotermes formosanus	Formosan subterranean termite	<9.3°C	Inactive	Active at temperatures from 9.3 to 38.1°C (Ricardson and Sun, 2023)
		9.3-38.1°C	Active temperature	
		>38.1°C	Inactive	

The interactive map shows areas in the UK that each temperature threshold is met per species at the 2°C and 4°C GWLs (see the following sections for more information on how GWLs were applied to the pest analysis). The map presents the percentage of time i.e., the percentage of days per year, during which the mean air temperature is projected to sit within each temperature threshold, indicating the level of exposure to the different levels of pest development, as defined in the table above. For the biscuit beetle species, the map shows whether a location is projected to experience at least 490 degree days above baseline of 15°C, the amount of GDD required for one full lifecycle of the species, therefore indicating potential exposure to the development of the species.

Global Warming Levels and model selection

2°C and 4°C GWLs have been used in this analysis.

A climate model selection process has been undertaken to identify key models to use within the analysis. Using the UKCP18 mean air temperature data (Tmean), there are 12 climate models available that provide projections. Each climate model simulates the climate slightly differently, meaning they each project that the 2°C and 4°C GWLs will be reached at different periods. To reduce the number of models used, the model selection process identified the median model.

This means that amongst all 12 models, the identified model projects the median rate of change in Tmean across a 20 year period. Per model, the 20 year period that was analysed was the period that leads up to the year that model projects that the 2°C GWL will be met. The method used to conduct this model selection process is outlined in the following section below.

A.3.4.1 Calculation

Global Warming Levels and model selection

To identify the median model, the difference between the 20 year mean of the 1.5°C and 2°C GWLs was used, as advised by colleagues at The CCC. The reason for this was to identify the change that *leads up to* the initial GWL that we are using within the analysis (2°C). The method consisted of:

- Using the daily Tmean data to *calculate mean annual UK Tmean per model* over a total of 100 years (total 12 models)
- Calculate *mean over 20 year period* between the *start and end year of* the *1.5*°C GWL (for each of the 12 models, the CCC provided the start, central and end years at which each model projects the different GWL to be reached).
- Calculate *mean over 20 year period* between *start and end year of the 2*°C GWL
- Calculate the *difference* between 20 year period mean per model (between GWLs 1.5°C and 2°C)

  Identify the *median of the differences* to determine the 'median' model. As there are 12 models, the model ranked 6th, where ranked lowest to highest, was selected.

Exposure scores

Temperature thresholds

The pest exposure scores were calculated by using the mean air temperature data (Tmean) and applying the given temperature thresholds (Tthreshold) (see Table 24 above), to determine how much time, in a year, is projected to experience air temperatures below, within, and above the temperature thresholds per species. This is translated into the percentage of time projected to experience the different temperatures, i.e. the percentage of days per year. This was determined at the resolution of the mean air temperature data (daily, per 12km gid cell) for the specific years at each GWL for the selected climate models, and was calculated by identifying the following:

The number of days per year, per cell, where:

- Tmean < the lower Tthreshold
- Tmean = Tthreshold range(s)
- Tmean > the upper Tthreshold

The number of days projected to experience mean air temperature at each threshold is summed, per grid, to provide an annual indication of pest development.

This was coded and calculated within Geographical Information Systems (GIS) software.

Growing Degree Days

For the *Stegobium paniceum* (biscuit beetle) species, GDD was calculated to represent the number of lifecycles, per year, that are projected to occur based on mean air temperature projections. The life cycle of insects do not align with a calendar year, and may take longer, or shorter, than a year for a full lifecycle to be realised and still result in exposure, meaning that it is possible for a partial lifecycle to be presented on the map. For example, one full lifecycle equates to 490 GDD in a year, so 245 GDD in a year equates to 0.5 lifecycles per annum, indicating exposure to a 2 year lifecycle.

GDD was calculated using the following equation and steps per grid:

1. GDD = Tmean - Tbase (where Tmean is the mean air temperature and Tbase is the minimum temperature at which a species can develop at a certain lifecycle stage). For this species, Tbase = 15°C for one full lifecycle.

   This was calculated at the resolution of the mean air temperature data (daily, per 12km gid cell).

2. Where Tmean = 15°C, GDD = 0. Each Tmean value above this equates to 1 additional GDD, e.g. where Tmean = 16°C, GDD = 1, and where Tmean = 20°C, GDD = 5. Per grid, each degree above the base value, for each daily average, is summed per year. The annual sum of GDD then provides an indication of whether pest development can occur. For this species, 490 GDD is required for one full lifecycle.
3. Each GDD value is divided by 490 to determine the number of lifecycles per annum to be presented on the map. Where annual GDD = 490, the map shows a value of 1, where GDD = 245 GDD, 0.5 is presented on the map, and where GDD = 735, 1.5 is shown, for

example, to contextualise the GDD information and indicate the number of potential lifecycles per annum and therefore potential exposure to pest development (Figure 11).

The assumptions and limitations associated with this methodology for pest exposure are outlined in Section 4.1.5.

Appendix 4 – Spatial mapping

Task 4 consisted of developing the final interactive map by using GIS to bring together the inputs gathered throughout the project, including the data collected and metrics developed in Tasks 2 and 3. This section provides an overview of the key steps taken to produce and communicate the final map.

A.4.0 Processing the data

In GIS (Geographic Information Systems), processing data refers to different techniques used to transform and manipulate spatial data to extract useful information and create maps. The datasets underwent preprocessing, including cleaning, formatting and georeferencing to ensure accurate spatial distribution of the hazards. Spatial analysis techniques were applied to calculate and apply exposure scores for each hazard, generating layers to be presented on the interactive map. ArcGIS, R and Python were used for automating parts of the data processing and layer creation workflows.

A.4.1 Presenting the map

The map was produced so that each hazard is represented as separate toggleable layers, which the user can select from the drop-down options. Distinct colour schemes were used for each hazard with colour-blind friendly colours, to ensure clear visual differentiation and accessibility for users. Layer legends are included to show the colour-code for the exposure scores. Interactive features, such as pop-ups, are included to provide detailed information for specific map areas when clicked. When a grid cell is clicked, the attribute table appears containing key attributes, such as the raw data that underpins the exposure scores. Tools for zooming, panning and layer toggling were configured to make navigation simple and user-friendly.

A.4.2 Hosting the map

The server used to host the map is part of an ArcGIS Enterprise deployment that is internal to Ricardo. Datasets were published onto the server to provide a quick user experience when querying and interacting with each data layer. By setting a reverse proxy and web context URL on the Enterprise deployment, user requests (such as switching a layer on/off) are intercepted and forwarded to the appropriate internal server. This allows an external URL to access an internal server. As the data sits ready on the server, the time it takes to request information through the interactive map is greatly reduced, providing a quick user experience. ArcGIS Enterprise provides users with clear functionality for data layers, such as the toggle buttons, and hosts these data layers as a map by directly linking to the published datasets on the server. Privacy settings allow for controlled access as the app is hosted on the server, so only permitted users (those with usernames and passwords) can view the data.

A.4.3 Updates based on feedback

Feedback sessions were conducted with the Steering Group to review the map's usability, clarity, and accuracy. Specific suggestions from the group were implemented, such as refining colour schemes, adding a feature to adjust the basemap, including a splash-screen to contextualise the data, and a Local Authority layer to enable the user to search by Local Authority.

A.4.4 User Workshop

A user workshop is being held (in mid-January 2025) to present the map and demonstrate how it works to the intended users. Participants will be guided through the map's features and questions will be taken throughout. Feedback from the workshop will be used to further enhance the user experience, but no further adjustments to data will be made.

A.4.5 User Guide

A comprehensive user guide has been developed to accompany the map, providing instructions on accessing, navigating, and interpreting the map. It includes an abbreviations log to help the user better understand the terminology being used.

Appendix 5 – REA of potential adaptation options

This section provides an overview of potential adaptation options to address the sensitivities of different building categories in relation to five climate-related hazards: extreme wind, wind-driven rain (WDR), subsidence, wildfires, and pests. The analysis is organised into five tables, each detailing adaptation options for different building types, fabric, design, and age.

A.5.0 Extreme wind

Table 30 Potential adaptation options for extreme wind (ordered by building categories)

Category	Potential adaptation options for extreme wind
Building type	Review and update building codes and standards to **consider potential future load** from climate-driven extreme wind (T14, T19, T95). Amend guidelines and regulation to ensure new and retrofitted buildings have the appropriate design characteristics and limitations for a future with more severe storms. It is important that revised or new regulatory change considers the differential impacts on varying population groups to ensure equitable outcomes (i.e. cost burden placed on individuals) (T19). Ensure that design standards applying to **manufactured home estates** and **caravan parks** have suitable protection for extreme storm events (T19) such as windbreaks or roll-down shutters on windows and doors to improve the protection of property to wind and debris (T57, T58). **Create windbreaks**: Plant suitable vegetation and trees to create windbreaks in areas surrounding the settlement to reduce wind exposure (T1, T2).
Building fabric	**Energy-efficient windows with retrofit films can improve resistance to breakage** from wind-borne debris, e.g. windows with double-glazing with one low e-coating take 3-4 times longer to break than ordinary double-glazed windows (F003). For highly exposed buildings, susceptible to extreme impacts, damage-resistant stainless steel screen systems, consisting of a heavy gauge stainless steel screen mesh, can be installed over the window to be protected (F009). In traditional buildings (that use slates, plain clay tiles, or pantiles), using **underlay and additional slate securing** methods (cheek nailing) can ensure the roof remains watertight during storms (F026).

Category	Potential adaptation options for extreme wind
	For coastal regions, **regular maintenance** of metal components (e.g., maintaining mortar joints, repainting, re-coating of ironwork) can **reduce the effect of salt spray-induced corrosion** or help to **maintain structural integrity following corrosion** (F026).
Building design	Increase the rigidity of supporting members (e.g. sashes) helps to **improve the wind resistant performance of glass**. Installation of **window shutters can protect against wind-borne debris** for windows and walls (D46, 48, 50). **Installing metal shutters** on lower levels of tall buildings can also **protect against wind-borne debris**. Additionally, the use of **glass with an internal plastic film** is effective in **preventing escalation of damage** if the window is hit by wind-borne debris. (D46, 53) Wind loads on new buildings can be reduced by introducing more aerodynamically efficient design features that helps to minimise wind loads, i.e. using **curved corners**, minimising the overhang of **eaves**. (D61) Designing roof structures to better withstand windstorms (e.g. dome shaped structures or Egypt and Japan) can also help to **resist wind damage by improving aerodynamics**, minimising wind forces (T12, T72). **Retrofit the building** envelope and structural framing by either **strengthening all connections in the vertical and lateral load paths** and/or **establishing mechanical connections of the exterior corner joints** (and joints between interior partitions and exterior walls) (T14).
Building age	**Regular checking/ monitoring** of the building, and additional checks after storms occur. (A96). Ensure essential maintenance is carried out, potentially by changing behaviours of building owners (A5, A30, A32, A96). This includes ensuring guttering, tiles and chimneys are secure (A39). Maintaining and renewing thatch grass in historic thatch roofs offers protection from strong winds (A32, A66). On turrets and exposed areas, cheek nailing is sometimes necessary for every course. Cheek nailing consists of securing slates with additional nails along their sides (A16, A30). In some parts of Scotland where larger slates are used they are fastened with two nails on each slate, in the English way. In this case additional nailing is not normally required” (A30)

Category	Potential adaptation options for extreme wind
	For **churches** "in order to preserve their integrity, it is not enough to better connect them to the masonry structure, but it is essential to ensure a better connection between the upper and inferior part of the roof structure" (A14). To prevent structural failures caused by wind loading, its important to create a continuous load path between the roof and the main **structural wall" on heritage buildings.** However, "in places where wind is projected to increase its gusts, and bearing capacity of roof components might be exceeded, it is **important to consider the structural components**, such as struts" (A39). Addition of storm glazing for additional protection of openings (doors windows etc) of **older buildings** (A30, A39).

A.5.1 Wind-driven rain

Table 31 Potential adaptation options for wind-driven rain (WDR) (ordered by building categories)

Category	Potential adaptation options for wind-driven rain (WDR)
Building type	**Install roll-down shutters** that make solid contact with the windowsill or ground as these provide full protection from wind-driven rain, water ingress, and damage, regardless of direction or wind speed (T58). **Regularly inspect and monitor building elements** that are sensitive to wind-driven rain, particularly rainwater systems (e.g. drainage pipes) and areas that may experience water ingress. Check for damage to rainwater systems and any signs of water ingress and perform repairs (T161). **Ensure that wind-driven rain is considered when developing and designing new properties**. The international standard EN-ISO 15927-3 provides estimates of the amount of water that may impact walls based on their orientation and offers two methods for calculating driving rain index for vertical surfaces (T82).
Building fabric	**Revise building standards to have stricter regulation** on envelop construction, finishing materials, and insulation types (F014, F053, F058). **Improve monitoring** through use of non-destructive electromagnetic sensory detection (F016) and use this to inform **more frequent maintenance** (F026).

Category	Potential adaptation options for wind-driven rain (WDR)
	Use materials that are resistant to wind-driven rain or resilient to water ingress, that are durable, weather resistant, with the appropriate hygrothermal properties (F025, F029)**.** These include lime harling or lime-based renders for walls (F026, F027), capillary-active insulation materials (F025). **Improve roof junctions** to redirect water away from areas where it may collect and lead to water ingress (F027). **Use masonry protection** such as lime-based materials, “soft" capping, and wall reinforcement to limit moisture ingress (F027). **Use coatings and sealants on modern construction** to enhance material protection and limit moisture ingress, such as hydrophobic paint (F029). **Explore new technologies** such as self-healing materials such as paints which are able to fill and repair scratches and cracks (F029).
Building design	Minimise water penetration through the use of **hydrophobic cladding or coating of ventilated facades**, with a **ventilated airgap**. (D1, 2, 6, 14, 18, 28). **Consider roof slope** in the design of buildings. As roof slope increases the intrusion of wind-driven rain decreases (D13). At planning or development stage, include **roof overhangs, balconies, or orientating the wall** to direction with the least wind-driven rain exposure. While the complete elimination of water on the envelope is not practical, this can greatly reduce water ingress and/or damage (D27, D36). Consider using an **adhered** (continuous and seamless) **secondary water barrier** (underlayment), as this offers greater protection than barriers which were fastened or nailed (D13).
Building age	The key adaptation mentioned in most papers is ensuring high levels of building **maintenance** and **monitoring**. Examples of maintenance are: sealing joints, clearing and maintaining gutters, securing roof tiles (A5, A44, A48, A96)

Category	Potential adaptation options for wind-driven rain (WDR)
	Ensure rainwater goods are well maintained and are fit for purpose. They should be designed to cope with greater volumes of water and keep the water away from the building fabric. (A5) **Addition of detailing** to buildings and more cover for exposed walls (A5, A57, A96). Or **addition of external cladding** (e.g. a slate hanging) to protect particularly vulnerable walls. (A30, A96) For concreate walls a coating can be added to the surface (A57). Lead capping can also be considered (A96) Minimise run-off onto the gable, water can be redirected "i) the cut of edge slates with an angle on the edge corner of a free overhang roof junction with the verge in order to redirect water towards the middle of the next slate; ii) a lead skew or a watergate (alias secret gutter) for vulnerable junctions" (A39) **Thinner insulation assemblies** such as calcium silicate could be considered for solid wall retrofits. (A27) **Traditional materials** should be considered for maintenance for example lime harling or breathable lime-based render is better suited than cement renders which can lead to more moisture issues in the building (A30, A96) **Ensure regular monitoring and control** of indoor humidity (A5, A43). **Use heating at strategic locations within the building** to encourage drying and prevent conditions where pests may thrive. For example, at Blickling Hall conservation, heating is used in parts of the building that house sensitive collections, to reduce the indoor relative humidity levels and thus eliminate susceptibility to mould growth and other biodeterioration (A43). Sealing windows and adding overhanging eaves to protect windows and openings (A25). **Addition of storm glazing to protect windows** from WDR or External Protective Glazing (EPG) especially for historic stained glass windows. Sol-gel coating can also be considered (A30, A39) **Weather stripping of windows** can reduce penetration of WDR. (A30)

Category	Potential adaptation options for wind-driven rain (WDR)
	In exposed areas WDR can be blown up under slates, an **underlay** should be used in these areas to ensure the roof is watertight. (A30)

A.5.2 Subsidence

Table 32 Potential adaptation options for subsidence (ordered by building categories)

Category	Potential adaptation options for subsidence
Building type	Provide information and support on subsidence to those who care for **historic buildings**, including owners, communities, local authorities and volunteers (T36). Enhance building guidelines with planning and ground evaluations for new buildings to determine the appropriate foundation types to reduce sensitivity to shrink-swell conditions (T102, T110, T114, T168). Building guidelines should incorporate regulations concerning both existing and planned vegetation. For **buildings situated in clay-rich soils** near trees or large hedges, the foundation depth should be at a certain level to reduce the risk of subsidence. (Partners, BGS). Employ measures to **improve water drainage** away from properties to avoid water saturation of foundations (T161). **Managing trees near buildings** is crucial to minimize subsidence caused by root systems removing moisture from the ground. A ban on planning within a certain distance from existing trees could be an option (Input from Project Steering Group).
Building fabric	**Communities possess valuable insights** into local climate conditions, building materials, and traditional construction techniques, which can inform adaptation strategies. They can also play a crucial role in developing and testing innovative solutions to address the challenges of building preservation. Preserving and transmitting traditional building knowledge across generations is **essential for maintaining adaptive capacity** (F083). The specific construction methods and techniques employed in earthen buildings influence their susceptibility to subsidence. For instance, the presence of a **protective roof or shelter** can mitigate top-down erosion (F083).
Building design	Potential problems to **foundations** could be addressed through higher specification of foundations, including greater depths, as well as by new construction methods (D69, 73, 78). **Strengthening of foundations**; classic underpinning ii) mini-piled and root piles iii) lime piles and iv) injection of resins, e.g. polyurethane. (It is important to note that polyurethane injection

Category	Potential adaptation options for subsidence
	technology does not require any injection pressure, making it a promising approach for enhancing the stability of shallow foundations of historical buildings. However, more research needs to be done on its long-term results in heritage buildings cases.)" (A39). Strengthening foundations through underpinning or building deeper foundations can enhance the stability of buildings where subsidence is apparent and there is evidence of insufficient foundations. However, this option is **expensive and carbon intensive** and not possible where infrastructure services are underground (Input from Project Steering Group).
Building age	**Strengthening foundations** through underpinning or building deeper foundations can enhance the stability of buildings e.g. the Sagrario Church and Columbus Library in Seville demonstrate the severe consequences of shrink-swell on historic buildings, requiring extensive repair work (F057). However, this is **expensive and carbon intensive** and not possible where infrastructure services are underground (Input from Project Steering Group). Take preventative measures to **improve drainage** of water away from the building's foundations and walls. (A96) **Monitor walls and foundations** for signs of cracking especially after floods and drought periods. (A96) "a vertical cut-off wall, which is a thin, continuous concrete wall of at least 1.5 m deep, may be installed beside the building to redistribute and equilibrate soil moisture conditions and hold root plants far from the surrounding building area" (A39).

A.5.3 Wildfires

Table 33 Potential adaptation options for wildfires (ordered by building categories)

Category	Potential adaptation options for wildfires
Building type	**Create firebreaks** between natural vegetation and residential areas to prevent wildfires spreading to built environment (T1, T116, T134). Improve and enforce building codes and regulations, ensuring that buildings meet the requirements to reduce sensitivity to wildfires and discourage **residential development** in fire-prone areas (T95, T116, T134, T135, T138, T145). Implement **fuel management strategies** (e.g. fuel reduction) to minimise the sensitivity of built assets to wildfire (T141).

Category	Potential adaptation options for wildfires
	Use cladding/roofing types that are more resistant to embers that are cast from forest fires and can contribute to fire ingress into **urban areas** (particularly in the US) (Partners). **Regularly clean gutters** to remove leaves and other flammable materials, which can act as fuel for wildfires (Type, Fabric, Design). **Adequate maintenance of live and dead vegetation** in buildings' immediate surrounding to prevent fire spread (Type, Design).
Building fabric	**Material Selection:** Prioritise non-combustible or fire-resistant materials, such as masonry (particularly hollow brick), concrete, gypsum board and certain metals (F001, F004, F062, F067 F089). Thicker, denser timbers can increase time required for fire penetration (F060). Choosing cladding materials with high reflectivity and low thermal conductivity, such as cardboard and fibreboard with a density of 1000 kg/m³, can enhance fire resistance (F063). **Insulation Selection:** Choose insulation materials with high thermal resistance and low flammability (F070, F072). **Material Treatments:** Apply fire-retardant treatments to combustible materials (F065, F066, F074) or intumescent coatings – delays temp rise, reduces evaporation of pyrolysis gases and oxygen to the surface (F065, F066). Note negative impacts of treatments including increased hygroscopicity, reduced strength, dimensional instability, corrosion of fixings, coating adhesion (F065). **Drencher systems:** have been proposed to prevent fire spread on thatched roofs and has been successfully tested in firebrand shower exposure experiment (F098). A non-combustible eave consisting of a non-combustible window overhang under the thatched roof has also been considered (F098). **Prefabrication/composite assemblies:** Aerogel coupled with resin coated ceramics could keep temperatures safe on the interior of a building while the exterior temperature exceeds 760 °C (F004). **New materials:** A silica-based aerogel porous board presents a promising solution for enhancing building energy efficiency and fire safety (F069).
Building design	Exterior non-constructive elements such as **balconies, porches, or decks** should not be made of flammable materials. (D97)

Category	Potential adaptation options for wildfires
	Adequate maintenance of live and dead vegetation in buildings' immediate surrounding, **non-combustible fences, timber fences regularly wetted, and non-combustible retaining walls, paths and gravel borders** appeared to be effective in preventing fire spread. (D93)
Building age	**Options to minimise damage from fires to historic buildings:** Have an **emergency response** plan and discuss this with the local fire brigade, this should include priority rooms/ items to salvage. And how to act in different scenarios. Conduct drills on a regular basis (A32, A101) Have **fire blankets or tarpaulins** for items that are less easy to move/ dismantle. (A32) Have **fire detection systems** and retrofit the building to meet fire safety requirement, consider adding a **sprinkler system** (A101)

A.5.4 Pests

Table 34 Potential adaptation options for pests (ordered by building categories)

Category	Potential adaptation options for pests
Building type	**Evidence gap:** no potential adaptation options found in the literature relating to building type.
Building fabric	Preventing water ingress can mitigate the risk of biological colonisation (F081). Waterproof coatings are not a reliable option given the risk of future damage by other processes but reducing water ingress by good maintenance and appropraite materials will reduce this risk. **Conduct routine monitoring** for the presence of deathwatch beetles more frequently in autumn and winter (D118). Similarly, choosing materials **with low water absorption and good durability** can reduce the susceptibility of the building fabric to wind-driven rain and subsequent biological damage (large amount of pores with diameters below 0.1µm (F081). **Shields**: Metal or plastic termite shields have been used as a replacement for the concrete cap or other methods of sealing masonry foundations. If properly designed, constructed, installed, and maintained, shields will **force termites out into the open**, revealing any tunnels constructed around the edge and over the upper surface of the shield. Experience has shown, however, that **very few shields are properly constructed and installed** and that homeowners usually fail to inspect shields frequently enough to detect termite infestations. The shields make infestations easier to detect, but do not provide effective protection and **should not be solely**

Category	Potential adaptation options for pests
	relied upon to control termites. In recent years stainless steel mesh and plastic physical barriers have been introduced (F075) Some physical barriers are impregnated with insecticide to provide even more protection. The use of **soil-applied insecticides** during construction is the most widely employed method of preventing termites and has a long history of success. Use of **pressure-treated lumber** is another successful practice, but termites may tunnel over treated wood to reach untreated wood elsewhere (F075). Development and use of new, innovative materials with **slow controlled release of biocides** (F081).
Building design	**Evidence gap:** no potential adaptation options found in the literature relating to building design.
Building age	**Use heating at strategic locations within the building** to encourage drying and prevent conditions where pests may thrive. For example, at Blickling Hall conservation heating is used in parts of the building that house sensitive collections, to reduce the indoor relative humidity levels and thus eliminate susceptibility to mould growth and other biodeterioration (A43). **Conservation heating** will decrease damage from pests that depend on humidity, but for pests that are not influenced by humidity an increase in temperature could increase their activity. (A79) Ensure constant monitoring, for example, the **Insect Pest Management Programme (IPM)** run by English Heritage may help in early detection. (A102)

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F081	Nijland, Timo G; Adan, Olaf CG; Van Hees, Rob PJ; van Etten, Bas D;	2009	Evaluation of the effects of expected climate change on the durability of building materials with suggestions for adaptation	https://publications.tno.nl/publication/34609719/Gbfsny/nijland-2009-evaluation.pdf
F082	Richards, Jenny; Brimblecombe, Peter;	2022	Moisture as a driver of long-term threats to timber Heritage—part I:	https://www.mdpi.com/2571-9408/5/3/100

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F083	Nakhaei Ashtari, Masoud; Correia, Mariana;	2022	Assessment of vulnerability and site adaptive capacity to the risk of climate change: the case of Tchogha Zanbil World Heritage earthen site in Iran	https://www.emerald.com/insight/content/doi/10.1108/JCHMSD-06-2021-0108/full/html
F084	Brimblecombe, Peter; Lefèvre, Roger-Alexandre;	2021	Weathering of materials at Notre-Dame from changes in air pollution and climate in Paris, 1325–2090	https://www.sciencedirect.com/science/article/pii/S1296207421000996
F085	Sahyoun, Sahar; Wang, Lin; Ge, Hua; Defo, Maurice; Lacasse, Michael;	2020	Durability of internally insulated historical solid masonry under future climates: A stochastic approach	https://pdfs.semanticscholar.org/f374/ac24486decc6a396fe7d1829f1d8674167a8.pdf
F086	Köliö, Arto; Pakkala, Toni A; Lahdensivu, Jukka; Kiviste, Mihkel;	2014	Durability demands related to carbonation induced corrosion for Finnish concrete buildings in changing climate	https://www.sciencedirect.com/science/article/pii/S0141029614000467
F088	Viles, Heather A;	2002	Implications of future climate change for stone deterioration	https://www.lyellcollection.org/doi/abs/10.1144/GSL.SP.2002.205.01.29
F089	Vagtholm, Rune; Matteo, Amy; Vand, Behrang; Tupenaite, Laura;	2023	Evolution and current state of building materials, construction methods, and building regulations in the UK: implications for sustainable building practices	https://www.mdpi.com/2075-5309/13/6/1480
F090	DESNZ	2023	Risk of Damage to Building Fabric from Climate Change	https://ricardogroup.sharepoint.com/:w:/s/CSN0WHazardMapping-RPLC-EXT/ERRpZHy-BCFJvHjnDG8n4z4BGbUoZcNQ0Yuq3f8lc8NwzQ?e=5BkUb3
F091	National Trust		Historic Building Fabric	https://ricardogroup.sharepoint.com/:b:/s/CSN0WHazardMapping-RPLC-EXT/EbUiDx54C8dLuhAlUaZYeiUBGoyPPzimKBGuds1sKGXMPQ?e=qXpPeP

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F092	Brimblecombe, Peter		Predicting the changing insect threat in the UK heritage environment	https://ricardogroup.sharepoint.com/:w:/s/CSN0WHazardMapping-RPLC-EXT/EY6n0Hc4iFdPkSGEtcCVKZgBIJwsMHEYx1dMqP_rost4yw?e=Bxbiip
F093	Maraveas, C.	2015	FIRE RESISTANCE OF METAL FRAMED HISTORICAL STRUCTURES	https://ricardogroup.sharepoint.com/:b:/s/CSN0WHazardMapping-RPLC-EXT/EXeH0AMnukZCiEfbrvyphEcBS-hfeDZhxNnbYGY2pFTR6w?e=fRmC69
F094	Emery, S.	2022	Research into the change in compressive strength of limestone due to heating	https://ricardogroup.sharepoint.com/:b:/s/CSN0WHazardMapping-RPLC-EXT/EVgWm5N18OxMI6jx-q93nVUBljkGDm0-RiGa6RWo_IPk7Q?e=ByCUcI
F095	Sasinka, B.	2014	FIRE-DAMAGED STONE: THE EFFECTS OF HEAT, FLAME, & QUENCHING	https://ricardogroup.sharepoint.com/:b:/s/CSN0WHazardMapping-RPLC-EXT/EXq_UZOTIJ5MgDeiUQL5fnIB2KLrArGnJCikuKD31ZR0kg?e=MLmYJn
F096	Groot, C.	2010	The influence of materials characteristics and workmanship on rain penetration in historic fired clay brick masonry	https://www.researchgate.net/publication/254889778_The_influence_of_materials_characteristics_and_workmanship_on_rain_penetration_in_historic_fired_clay_brick_masonry
F097	Bunnik, Ton; De Clercq, H; van Hees, RPJ; Schellen, HL; Schueremans, Luc;	2010	Effect of climate change on built heritage	https://research.tue.nl/files/42097980/Metis235825.pdf
D1	Tiittanen, Antti;	2021	Hygrothermal Performance of Sandwich-Panel-Renovated External Walls	https://trepo.tuni.fi/handle/10024/136211

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D2	Hansen, Tessa Kvist;	2019	Hygrothermal performance of internal insulation in historic buildings	https://vbn.aau.dk/en/publications/hygrothermal-performance-of-internal-insulation-in-historic-build
D4	Rovers, Ronald; Morck, Ove; Lupisek, Antonin; Pihelo, Peep; Kuusk, Kalle; Kalamees, Targo; Kamphuis, Jan; van Oorschot, John; Almeida, Manuela; Borodinecs, Anatolijs;	2017	WP3: Deliverable 3.8: Guide with concepts of renovation packages for different types of building	MORE-CONNECT_WP3_D3.8-Guide-with-renovation-concepts.pdf
D5	Ueno, Kohta;	2010	Residential exterior wall superinsulation retrofit details and analysis	https://www.appliedbuildingtech.com/system/files/cp-1012-residential_exterior_wall_superinsulation_retrofit_details_analysis.pdf
D6	Recatala, Maria Arce; Morales, Soledad Garcia; Van Den Bossche, Nathan;	2018	Experimental assessment of rainwater management of a ventilated façade	https://journals.sagepub.com/doi/abs/10.1177/1744259117719077
D7	Golding, Neil Richard;	2019	The establishment of a whole house analysis framework and process to design out unintended consequences in the energy retrofit of small-scale domestic traditional buildings	https://wsa-ondisplay.co.uk/wp-content/uploads/sites/2/2020/07/ART506-Neil_Golding.pdf
D10	Shahreza, Seyedmohammad Kahangi; Niklewski, Jonas; Molnár, Miklós;	2022	Novel water penetration criterion for clay brick masonry claddings	https://www.sciencedirect.com/science/article/pii/S0950061822027647
D11	Kvande, Tore; Lisø, Kim Robert;	2009	Climate adapted design of masonry structures	https://www.sciencedirect.com/science/article/abs/pii/S0360132309001036
D12	Curtis, Roger; Hunnisett Snow, Jessica;	2016	Short guide-Climate change adaptation for traditional buildings	http://eprints.sparaochbevara.se/882/
D13	Bitsuamlak, Girma T., Arindam Gan Chowdhury, and Dhawal Sambare.	2009	Application of a full-scale testing facility for assessing wind-driven-rain intrusion	https://www.sciencedirect.com/science/article/abs/pii/S0360132309001048
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D17	Little, Joseph; Ferrari, Calina; Arregi, Beñat;	2015	Assessing risks in insulation retrofits using hygrothermal software tools	https://arrow.tudublin.ie/bescharcrep/4/
D18	Künzel, Hartwig; Dewsbury, Mark;	2022	Moisture control design has to respond to all relevant hygrothermal loads	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10171418/
D20	Heritage, Ulster Architectural;	2022	Impacts of Climate Change on the Historic Built Environment	https://niopa.qub.ac.uk/bitstream/NIOPA/17488/1/dfc-impacts-of-climate-change-on-historic-built-environment-2021.pdf
D21	Cox-Smith, Ian; Overton, Greg E;	2020	Linings-on Retrofit Insulation in Weatherboard Walls: Ensuring Effective Water Management	https://d39d3mj7qio96p.cloudfront.net/media/documents/SR436_Linings-on_retrofit_insulation_in_weatherboard_walls.pdf
D23	Aggarwal, Chetan;	2023	Development of climate-based indices for assessing the hygrothermal performance of wood frame walls under historical and future climates	https://spectrum.library.concordia.ca/id/eprint/991958/
D26	Barrelas, J; Ren, Q; Pereira, C;	2021	Implications of climate change in the implementation of maintenance planning and use of building inspection systems	https://www.sciencedirect.com/science/article/abs/pii/S2352710221006355
D27	Moghtadernejad, Saviz; Chouinard, Luc E; Mirza, M Saeed;	2020	Design strategies using multi-criteria decision-making tools to enhance the performance of building façades	https://www.sciencedirect.com/science/article/abs/pii/S235271021931959X
D28	Sivolova, Julija; Gremmelspacher, Jonas;	2019	FUTURE CLIMATE RESILIENCE OF ENERGY-EFFICIENT RETROFIT PROJECTS IN CENTRAL EUROPE	https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8985440&fileOId=8985486
D29	Skeie, Kristian; Gustavsen, Arild;	2021	Utilising Open Geospatial Data to Refine Weather Variables for Building	https://www.mdpi.com/1996-1073/14/4/802

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D30	Fedorova, Anna; Jelle, Bjørn Petter; Andenæs, Erlend; Imenes, Anne Gerd; Aunrønning, Ole; Schlemminger, Christian; Geving, Stig;	2010	Large-scale laboratory investigation of building integrated photovoltaics–a review of methods and opportunities	https://europedirect.cut.ac.cy/wp-content/uploads/sites/13/2017/03/30..pdf
D31	Siponmaa, Iida;	2021	Climate Resilience in Architecture	Climate Resilience in Architecture - Trepo (tuni.fi)
D32	Hao, Lingjun;	2019	Exploring the performance of historic residential building in South Tyrol: considerations on present and future climate	https://www.politesi.polimi.it/handle/10589/166681
D33	Gholami, Hassan; Nils Røstvik, Harald; Steemers, Koen;	2021	The contribution of building-integrated photovoltaics (BIPV) to the concept of nearly zero-energy cities in Europe: Potential and challenges ahead	https://www.mdpi.com/1996-1073/14/19/6015
D35	Dyer, Mark;	2016	Adaptable housing design for climate change adaptation	https://www.researchgate.net/profile/Oliver-Kinnane/publication/299660227_Adaptable_housing_design_for_climate_change_adaptation/links/58158bfd08aeffbed6be4af1/Adaptable-housing-design-for-climate-change-adaptation.pdf
D36	Jelle, Bjørn Petter;	2012	Accelerated climate ageing of building materials, components and structures in the laboratory	https://link.springer.com/article/10.1007/s10853-012-6349-7
D37	Andenæs, Erlend;	2021	Risk assessment of blue-green roofs	https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2825004/Erlend%20Anden%C3%A6s_PhD.pdf?sequence=1

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D38	van Hooff, Twan AJ; Schellen, Henk L; Havinga, Lisanne C;	2022	Hygrothermal analysis of applying internal insulation and hydrophobization in historic dwellings	Burg_van_den_0742415_ABP_Hooff_v.pdf (tue.nl)
D39	Cattano, Corey;	2013	Development of a Rating System to Measure the Vulnerability of Residential Homes to Natural Hazards	https://tigerprints.clemson.edu/all_dissertations/1161/
D41	Sandink, Dan; Kopp, Gregory; Stevenson, Sarah; Dale, Natalie;	2019	Increasing high wind safety for Canadian homes: A foundational document for low-rise residential and small buildings	ICLR-Western-SCC-Increasing-High-Wind-Safety-2019_EN.pdf
D42	Qin, Hao;	2020	Risk assessment and mitigation for Australian contemporary houses subjected to non-cyclonic windstorms	https://nova.newcastle.edu.au/vital/access/services/Download/uon:37028/ATTACHMENT01
D44	Pipinato, Alessio;	2023	Recent northeast Italian tornado events: lesson learned for improving structures	https://link.springer.com/article/10.1007/s11069-018-3380-2
D45	Tamura, Yukio;	2009	Wind-induced damage to buildings and disaster risk reduction	Design Resilient Building Strategies in Face of Climate Change | Semantic Scholar
D48	Mazzucchelli, Enrico; Scingi, Giacomo; Pastori, Sofia; Rigone, Paolo; Lucchini, Angelo; Trabucco, Dario; Milardi, Martino;	2022	Extreme wind events and risk mitigation: Overview and perspectives for resilient building envelopes design in the Italian context	https://air.iuav.it/handle/11578/322448
D55	Plumblee, Jeff; Klotz, Leidy;	2014	Marlo's windows: why it is a mistake to ignore hazard resistance in LCA	https://link.springer.com/article/10.1007/s11367-014-0741-2
D56	Qin, Hao; Stewart, Mark G;	2020	Risk-based cost-benefit analysis of climate adaptation measures for Australian contemporary houses under extreme winds	https://link.springer.com/article/10.1186/s43065-020-00002-1
D57	Stewart, Mark G; Ryan, Paraic C; Henderson, David J; Ginger, John D;	2016	Fragility analysis of roof damage to industrial buildings subject to extreme wind loading in non-cyclonic regions	https://www.sciencedirect.com/science/article/abs/pii/S0141029616307428

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D59	Sanders, CH; Phillipson, MC;	2003	UK adaptation strategy and technical measures: the impacts of climate change on buildings	https://www.tandfonline.com/doi/abs/10.1080/09613210320000097638
D63	Heritage, Ulster Architectural;	2022	Impacts of Climate Change on the Historic Built Environment	Impacts of Climate Change on the Historic Built Environment: A Report & Guide. (qub.ac.uk)
D65	Barrelas, J; Ren, Q; Pereira, C;	2021	Implications of climate change in the implementation of maintenance planning and use of building inspection systems	https://www.sciencedirect.com/science/article/abs/pii/S2352710221006355
D67	Sanders, CH; Phillipson, MC;	2003	UK adaptation strategy and technical measures: the impacts of climate change on buildings	https://www.tandfonline.com/doi/abs/10.1080/09613210320000097638
D68	Jansen, Dirk;	2023	Land subsidence related damage to residential real estate and cost-effective adaptation strategies: From sinking to solutions: a methodological approach to assess the cost-effectiveness of adaptation strategies to counteract land subsidence related damage to residential real estate	https://repository.tudelft.nl/islandora/object/uuid:fda6b963-ad2f-4e52-9b51-17619c6cd325
D69	Toll, DG; Abedin, Z; Buma, J; Cui, Y; Osman, AS; Phoon, KK;	2012	The impact of changes in the water table and soil moisture on structural stability of buildings and foundation systems: systematic review CEE10-005 (SR90)	https://durham-repository.worktribe.com/output/1636508
D70	Qiao, Xiaojun;	2023	Geospatial Monitoring and Assessment of Coastal Land Subsidence	https://www.proquest.com/openview/416f28f54012f64721b0cf5589ed76ab/1?pq-origsite=gscholar&cbl=18750&diss=y

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D74	Kazmierczak, Aleksandra; Carter, Jeremy;	2010	Adaptation to climate change using green and blue infrastructure. A database of case studies	https://orca.cardiff.ac.uk/id/eprint/64906/1/Database_Final_no_hyperlinks.pdf
D76	Sarıcıoğlu, PELİN; Aycam, İdil; Ulukavak Harputlugil, Gülsu;	2024	Analysis of Condensation Risk in A Wall Section in the Context of Climate Change Scenarios	https://avesis.gazi.edu.tr/yayin/afa9dd53-5309-49dd-b06b-6b5655df208c/analysis-of-condensation-risk-in-a-wall-section-in-the-context-of-climate-change-scenarios
D77	Smyth, David;	2012	Climate change and its potential impacts on construction in Ireland: the argument for mitigation and adaptation	https://mural.maynoothuniversity.ie/4388/
D78	Myronyk, Danielle Nastassja Marie;	2022	Saving Architectural Heritage: Climate Change Resilience and Conservation Management	https://repository.library.carleton.ca/concern/etds/79407x99q
D79	Barrelas, Joana; Silva, Ana; de Brito, Jorge; Tadeu, António;	2023	Effects of Climate Change on Rendered Façades: Expected Degradation in a Progressively Warmer and Drier Climate—A Review Based on the Literature	https://www.mdpi.com/2075-5309/13/2/352
D80	Linares, Rogelio; Roqué, Carles; Gutiérrez, Francisco; Zarroca, Mario; Carbonel, Domingo; Bach, Joan; Fabregat, Ivan;	2017	The impact of droughts and climate change on sinkhole occurrence. A case study from the evaporite karst of the Fluvia Valley, NE Spain	https://www.sciencedirect.com/science/article/abs/pii/S0048969716325293
D82	Mushta, Maryna Andriivna;	2021	Adaptation of the Kyiv city ecosystem to climate changes	https://dspace.nau.edu.ua/handle/NAU/54921
D84	Spennemann, Dirk HR;	2022	Earth to Earth: Patterns of Environmental Decay Affecting Modern Pisé Walls	https://www.mdpi.com/2075-5309/12/6/748
D85	ElDin, Nadeen Nour;	2023	Biomimetic Approach for Building Envelope	https://ojs.wiserpub.com/index.php/GBCE/article/view/2270

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D86	Committee on Adaptation to a Changing Climate;	2015	Adapting infrastructure and civil engineering practice to a changing climate	https://ascelibrary.org/doi/pdf/10.1061/9780784479193?download=true
D89	Intini, Paolo; Ronchi, Enrico; Gwynne, Steve MV; Bénichou, Noureddine;	2017	A review of design guidance on wildland urban interface fires	https://portal.research.lu.se/en/publications/a-review-of-design-guidance-on-wildland-urban-interface-fires
D90	Hakes, Raquel SP; Caton, Sara E; Gorham, Daniel J; Gollner, Michael J;	2017	A review of pathways for building fire spread in the wildland urban interface part II: response of components and systems and mitigation strategies in the United States	https://link.springer.com/article/10.1007/s10694-016-0601-7
D91	Leonard, Justin; Blanchi, Raphaele; Weir, Ian;	2020	Bushfire Resilient Building Guidance for Queensland Homes	https://eprints.qut.edu.au/207227/
D93	Laranjeira, João; Cruz, Helena;	2014	Building vulnerabilities to fires at the wildland urban interface	https://repositorio.lnec.pt/handle/123456789/1006732
D94	Roedel, Spencer;	2015	Designing for Disturbance: Adapting the Wildland Urban Interface to Wildland Fire	https://scholarsbank.uoregon.edu/xmlui/handle/1794/19097
D95	Figler, Mason;	2022	Assessing Wildfire Risk to the Built Environment at the YMCA	https://digital.wpi.edu/downloads/qz20sw90c
D96	Tihay-Felicelli, V; Barboni, T; Morandini, F; Santoni, PA; Pieri, A; Luciani, C; Martinent, B; Graziani, A; Perez-Ramirez, Y; Chiaramonti, N;	2023	Overview of the platform for experimentation and awareness-raising on fire risks at wildland urban interfaces (EXPLORII platform)	https://www.sciencedirect.com/science/article/abs/pii/S2212420923004600
D97	Arruda, Mário Rui Tiago; Bicelli, António Renato A; Branco, Fernando;	2024	Ignition Locations and Simplified Design Guidelines for Enhancing the Resilience of Dwellings against Wildland Fires	https://www.mdpi.com/2571-6255/7/2/40
D98	Kovacs, Paul;	2018	Development permits: An emerging policy instrument for local governments to manage	https://www.iclr.org/wp-content/uploads/2018/05/Development-Permits_2018.pdf

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D99	Baitch, Brenden;	2021	Firesafe: Designing for Fire-Resilient Communities in the American West	https://scholarworks.umass.edu/entities/publication/42b87eab-44b4-44f8-b6d5-71af6a879d73
D100	Arruda, MRT; Bicelli, ARA; Cantor, P; Assis, EB; Branco, F;	2023	Proposal of a fireproof design code for dwellings against the action of wildland fires	https://www.sciencedirect.com/science/article/pii/S2772741623000509
D101	Calkin, David; Price, Owen; Salis, Michele;	2020	WUI risk assessment at the landscape level	https://link.springer.com/referenceworkentry/10.1007/978-3-319-52090-2_97
D103	BASTEM, Elif; SOYLUK, Asena;	2023	Compilation of Architecture Design Guidelines for Residental Buildings in Wildfire Zones	https://www.bidgeyayinlari.com.tr/wp-content/uploads/2024/01/Mimarlik-ingilizce-2.pdf#page=34
D105	Schrader, Rebekah;	2023	Experimental Study of Heat Transfer Through Window Assemblies Under External Heat Flux	https://www.proquest.com/openview/16faac7892dc3a566231b3669ca9d7e7/1?pq-origsite=gscholar&cbl=18750&diss=y
D106	Chakraborty, Anusheema; Chesher, Barney; Dibis, Fawzi; Issa, Nivine;	2019	Urban resilience: A look into global climate change impacts and possible design mitigation	https://aesg.com/perspective/urban-resilience-a-look-into-global-climate-change-impacts-and-possible-design-mitigation/
D107	Wong, Gwendolyn KL; Jim, Chi Yung;	2016	Do vegetated rooftops attract more mosquitoes? Monitoring disease vector abundance on urban green roofs	Do vegetated rooftops attract more mosquitoes? Monitoring disease vector abundance on urban green roofs - ScienceDirect
D108	Carroll, Paul; Aarrevaara, Eeva;	2018	Review of potential risk factors of cultural heritage sites and initial modelling for adaptation to climate change	https://www.mdpi.com/2076-3263/8/9/322
D110	Kovats, R; Osborn, Dan;	2016	UK Climate Change Risk Assessment 2017: Evidence Report. Chapter 5: People & the built environment	https://discovery.ucl.ac.uk/id/eprint/1564649/

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D113	Querner, Pascal; Sterflinger, Katja; Derksen, Katharina; Leissner, Johanna; Landsberger, Bill; Hammer, Astrid; Brimblecombe, Peter;	2022	Climate change and its effects on indoor pests (insect and Fungi) in museums	https://www.mdpi.com/2225-1154/10/7/103
D115	Liao, Jhih-Rong; Tu, Wu-Chun; Chiu, Ming-Chih; Kuo, Mei-Hwa; Cheng, Hui-Ching; Chan, Chia-Chun; Dai, Shu-Mei;	2023	Joint influence of architectural and spatiotemporal factors on the presence of Aedes aegypti in urban environments	https://scijournals.onlinelibrary.wiley.com/doi/abs/10.1002/ps.7634
D116	Krishnankutty, Sindhu M; Bigsby, Kevin; Hastings, John; Takeuchi, Yu; Wu, Yunke; Lingafelter, Steven W; Nadel, Hannah; Myers, Scott W; Ray, Ann M;	2020	Predicting establishment potential of an invasive wood-boring beetle, Trichoferus campestris (Coleoptera: Cerambycidae) in the United States	Predicting Establishment Potential of an Invasive Wood-Boring Beetle, Trichoferus campestris (Coleoptera: Cerambycidae) in the United States | Annals of the Entomological Society of America | Oxford Academic (oup.com)
D117	Røskar, T;	2014	Old buildings in a new climate	https://d1wqtxts1xzle7.cloudfront.net/33353468/Old_buildings_in_a_new_climate-libre.pdf?1396317333=&response-content-disposition=inline%3B+filename%3DOld_buildings_in_a_new_climate.pdf&Expires=1718648038&Signature=Judy80E34GrPyXJzaAM2IjjlJMbuFPh1MBS8wXx~XDeNoijX69dtFHTF2E33p46fk2fa~qkaxOzORiX8-2Itw6b2hy67G8xpDWy2misoiWwyjFidptS1jPMIApR27WUJrmTvJy7ToHRRuY8u0OadK05fTVf~I2m6ZtBboM3K6-TTc6xHWOBFLWfn8h6YEZuNLAT7dIuT~gxILez4A63ze4C0GCLWqIINANZcDvezixeFWbZJmJLipNcci-O3Gra3~maYz8LZQPhvFFaAVs-

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D118	Brimblecombe, Peter; Richards, Jenny;	2022	Moisture as a driver of long-term threats to timber heritage—part II: risks imposed on structures at local sites	https://www.mdpi.com/2571-9408/5/4/154
A2	Erkal, Aykut; D'Ayala, Dina; Sequeira, Lourenço;	2012	Assessment of wind-driven rain impact, related surface erosion and surface strength reduction of historic building materials	https://www.sciencedirect.com/science/article/abs/pii/S0360132312001527
A3	Cassar, May; Pender, Robyn;	2003	Climate change and the historic environment	https://discovery.ucl.ac.uk/id/eprint/2082/1/2082.pdf
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A79	Lankester, Paul;	2013	The impact of climate change on historic interiors	https://ueaeprints.uea.ac.uk/id/eprint/42324/
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A90	Fluck, Hannah; Wiggins, Meredith;	2017	Climate change, heritage policy and practice in England: Risks and opportunities	https://www.repository.cam.ac.uk/items/255d80d9-4b70-489d-b0c4-8f2451378844
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A94	Kozlov, Valery; Kisternaya, Margarita;	2014	Biodeterioration of historic timber structures: A comparative analysis	https://www.tandfonline.com/doi/abs/10.1080/17480272.2014.894573
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A98	Peter Brimblecombe	?	Predicting the changing insect threat in the UK heritage environment	N/A
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T2	Okunola, Olasunkanmi Habeeb; Bako, Abdullateef Iyanda;	2023	Exploring residential characteristics as determinants of household adaptation to climate change in Lagos, Nigeria	EM-IJDR210049 1..17 (researchgate.net)
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T4	Goemans, Magdalene Cecilia;	2019	Bringing adaptation home: Citizen engagements with climate change at home site scales in Ottawa and Halifax	Etd | Bringing adaptation home: Citizen engagements with climate change at home site scales in Ottawa and Halifax | ID: rr171z08h | Hyrax (carleton.ca)
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T12	Faragallah, Riham Nady;	2021	Fundamentals of temporary dwelling solutions: A proposed sustainable model for design and construction	Fundamentals of temporary dwelling solutions: A proposed sustainable model for design and construction - ScienceDirect
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T16	Taylor, Jonathon; Mavrogianni, Anna; Davies, Michael; Wilkinson, P; Shrubsole, Clive; Hamilton, Ian; Oikonomou, Eleni; Biddulph, Phillip;	2016	Housing as a modifier of air contaminant and temperature exposure in Great Britain: A modelling framework	Housing as a modifier of air contaminant and temperature exposure in Great Britain: A modelling framework - UCL Discovery
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T18	Germain, Daniel;	2016	Snow avalanche hazard assessment and risk management in northern Quebec, eastern Canada	Snow avalanche hazard assessment and risk management in northern Quebec, eastern

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T37	Niklas, Sarah; Alexander, Dani; Dwyer, Scott;	2022	Resilient buildings and distributed energy: A grassroots community response to the climate emergency	Sustainability | Free Full-Text | Resilient Buildings and Distributed Energy: A Grassroots Community Response to the Climate Emergency (mdpi.com)
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T45	Nicolini, Elvira;	2024	Climate change adaptation and mitigation and historic centers preservation. Underway and repeatable technological design solutions	Climate change adaptation and mitigation and historic centers preservation. Underway and repeatable technological design solutions - ScienceDirect
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T54	Molua, Ernest L;	2010	Climate and location vulnerability in southwestern Cameroon: assessing the options and cost of protection to property in coastal areas	Discussion paper no 46 (dspacedirect.org)
T55	Council, Tipperary County;	2023	TIER 1 CLIMATE CHANGE RISK ASSESSMENT	5 .Wexford Climate Change Risk Assessment Tier 1.pdf (wexfordcoco.ie)
T56	Zhang, Fang;	2013	Flood damage and vulnerability assessment for Hurricane Sandy in New York City	OhioLINK ETD: Zhang, Fang
T57	Berman, Gregory; Simpson, Juliet;	2013	Massachusetts Homeowner's Handbook to Prepare for Coastal Hazards	Massachusetts Homeowner's Handbook to Prepare for Coastal Hazards (noaa.gov)
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T61	Stori, Fernanda Terra; O'Mahony, Cathal;	2021	Coastal climate adaptation in Ireland: The effects of climate change in Portrane (Fingal, Co. Dublin) and future perspectives	Coastal climate adaptation in Ireland: The effects of climate change in Portrane (Fingal, Co. Dublin) and future perspectives (ucc.ie)
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T63	Board, Gippsland Coastal;	2008	Climate Change, Sea Level Rise and Coastal Subsidence along the Gippsland Coast: Implications for geomorphological features	6026 FINAL Gipps Sea Level Change and Subsidence - Final Report vers2.1 May08.doc (psu.edu)
T65	TH, NAVIGATING; CONTOU, E; TH, SOF; HA, I; VER, E;	2007	S POLICY	Coverpage_Final.p65 (preventionweb.net)
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T72	Franz, Jamie;	2009	Volatile Waters: An Architecture of the Hurricane Coast	OhioLINK ETD: Franz, Jamie
T73	Gwilliam, Julie;	2007	Analysis of the potential impact of climatic change on risks to health and comfort for housing occupants in Neath Port Talbot, south Wales	Analysis of the potential impact of climatic change on risks to health and comfort for housing occupants in Neath Port Talbot, south Wales - ProQuest
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T77	Bengtsson, J; Hargreaves, R; Page, IC;	2007	STUDY REPORT	Study report SR179 Assessment of the need to adapt buildings in New Zealand to the impacts of climate change (d39d3mj7qio96p.cloudfront.net)
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T81	Davey, A		Traditional Buildings Health Check: changing behaviour around built heritage maintenance in Scotland	Adapting historic places to climate change: Proceedings of the international virtual conference of the project Adapt Northern Heritage: 05 & 06 May 2020
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T83	Pham, Lam; Ekambaram, Palaneeswaran; Stewart, Rodney A; Sahin, Oz; Bertone, Edoardo; Flores, Juliana Faria Correa Thompson;	2018	Resilient Buildings: Informing Maintenance for Long-term Sustainability	SBEnrc Project P1.53 Final Report - Part 3 (researchgate.net)

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T90	Bros Williamson, Julio;	2020	Impact of climate change and envelope performance dilapidation on dwellings	Impact of climate change and envelope performance dilapidation on dwellings (worktribe.com)
T91	Kelman, Ilan;	2003	Physical flood vulnerability of residential properties in coastal, eastern England	Microsoft Word - IlanKelmanPhDDissertation.doc
T92	Houghton, Edward; Kelly, Leanne; Raslan, Rokia; Cui, Cheng;	2024	Defining and identifying complex-to-decarbonise homes and retrofit solutions: Annex C–case studies	Defining and identifying complex-to-decarbonise homes and retrofit solutions: Annex C – case studies - UCL Discovery
T93	Tsoka, Stella; Thiis, Thomas K;	2018	Calculation of the driving rain wall factor using ray tracing	Calculation of the driving rain wall factor using ray tracing - ScienceDirect
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T96	Atkinson, Joanne;	2015	Evaluating retrofitted external wall insulation	Evaluating retrofitted external wall insulation
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T158	Michael G. Sanderson, Michael Eastman, Jason A. Lowe		Production of a gridded wind-driven rain dataset for the United Kingdom	
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T165	Harrison, A., White, J., Mansour, M., Wang, L., Mackay, J.D., Hulbert, A. and Hughes. A.G	2020	User Guide for the British Geological Survey GeoClimateUKCP18: Clay Shrink-Swell dataset. BGS GeoAnalytics & Modelling Programme, Open Report OR/20/013	GeoClimateUKCP18 User Guide - British Geological Survey (bgs.ac.uk)
T166	Peter Brimblecombe1 , Paul Lankester		Long-term changes in climate and insect damage in historic houses	untitled (english-heritage.org.uk)
T167	Paul Lankester	2013	The Impact of Climate Change on Historic Interiors	The impact of future climate on historic interiors (sciencedirectassets.com)
T168	Lee D Jones, Ian F Jefferson	2012	Expansive Soils	(PDF) Expansive Soils (researchgate.net)
T169	United Nations Environment Programme	2021	A Practical Guide to Climate-resilient Buildings & Communities	Adapbuild.pdf (unep.org)
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H013	British Geological Survey	2020	GeoIndex Onshore	GeoIndex - British Geological Survey
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