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Too hot, too wet, too dry? Global building stocks under extreme climate change

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Too hot, too wet, too dry? Global building stocks under extreme climate change

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Abstract

Climate change is increasing the frequency and severity of extreme weather events, creating growing pressures on the built environment. However, the quantity, composition and spatial distribution of building materials exposed to future climate hazards remain undetermined at the global scale. This study integrates global building stock estimates with projected climate hazards to quantify material exposure to extreme heat, fluvial flooding and drought under the SSP5-8.5 scenario for 2090-2100. Spatial analysis identifies regions exposed to individual and multiple hazards, alongside the quantities and composition of potentially affected materials. The results demonstrate substantial geographical heterogeneity, with prominent multi-hazard exposure across South, East and Southeast Asia, Australia, South America and the United States. Concrete (71.27Gt exposed to extreme heat, 43.45Gt - to drought and 26.76Gt to fluvial flooding) and brick (30.60Gt exposed to extreme heat, 23.71Gt - to drought and 13.75Gt - to fluvial floodings) dominate the exposed material stocks, reflecting their prevalence in the global built environment. By linking climate projections with building stocks, this study extends global climate exposure assessments to the material dimension of the built environment. The findings provide a foundation for targeted adaptation planning and future assessments of potential material recovery opportunities.

1 Introduction

Over the past century, anthropogenic greenhouse gas (GHG) emissions have driven significant changes in Earth's climate. This has resulted in a global average temperature increase approaching the 1.5°C threshold above pre-industrial levels (UNEP, 2026). These climate changes have driven an increase in the frequency and severity of adverse weather events, including heatwaves, wildfires, droughts and flooding (Seneviratne et al., 2021). Current climate models project likely end-of-century increases in global average temperatures between 1.5 and 4.8 degrees relative to 1850-1900 (Lee et al., 2021), resulting in yet more frequent and severe adverse weather events.

The effect of climate change on humans and human-made systems is both acute and chronic, including threats to health and life, long-term displacement, damage to physical infrastructure and associated economic loss (Handmer et al., 2012). The impacts of increased adverse weather events on global populations are increasingly understood through research into exposure (Maes et al., 2022), vulnerability (Turner et al., 2025; Notre Dame Global Adaptation Initiative, 2026), and associated risks to human health and well-being (Cissé et al., 2022), livelihoods (Birkmann et al., 2022), and settlements

(Dodman et al., 2022). In comparison, research on secondary implications for the built environments supporting these populations - and direct impacts thereon - remains comparatively limited.

Assessing these secondary implications, including the quantity and type of materials affected, requirements for adaptation, and potential for material recovery, requires a detailed understanding of global building and infrastructure stocks. This has been the focus of a significant portion of industrial ecology research over the past 20 years, with material stock and flow analysis (MSFA) being employed to quantify materials resident within (Tanikawa and Hashimoto, 2009; Fishman, Schandl, et al., 2014; H. Haberl et al., 2025) and flowing into and out of (Wiedenhofer, Steinberger, et al., 2015; Krausmann et al., 2017; Wiedenhofer, Fishman, et al., 2019) built environments of varying location and spatial scale (Lanau, Liu, et al., 2019; Fu et al., 2022).

Despite growing understanding of both built environment material stocks and the impact of climate change on global populations, consideration of these remains isolated, with the intersection of these research domains being the focus of only a handful of localised studies (Bradshaw et al., 2020; Martin del Campo et al., 2023; De Oliveira et al., 2026). This absence of forward-looking assessments of the vulnerability of global building stocks to climate hazards limits the evaluation of potential future risks, adaptation requirements and material recovery potential.

This paper represents the first step in understanding the impact of climate change on global building stocks by assessing the quantity, type and location of material exposed to a range of climate hazards. In doing so it (1) quantifies the material stocks in buildings projected to be exposed to extreme heat, fluvial flooding and drought globally, (2) analyses the material composition of this exposure across hazards and regions, and (3) explores the implications of this exposure for adaptation and material recovery. This reveals the substantial quantity and heterogeneous distribution of exposed materials, highlighting the need to incorporate the material dimension of the built environment into assessments of climate risk and adaptation.

2 Literature Review

2.1 Climate Change Risks

The consequences of climate hazards vary across the systems they interact with, some causing critical threats to the built environment and others - to its users. Changes in

precipitation can produce pluvial flooding that overwhelms drainage systems and disrupts transportation networks, while increased river discharge can generate severe fluvial flooding in inhabited areas, farmland and along critical infrastructure corridors (Caretta et al., 2022). High temperatures can exacerbate the urban heat island effect, increasing cooling energy demand and placing additional thermal stress on people (Dodman et al., 2022). Similarly, prolonged periods of high temperature and low precipitation can increase wildfire risk, with fires capable of affecting urban and rural areas, degrading air quality and damaging ecosystems (Parmesan et al., 2022). In coastal areas, sea-level rise increases the exposure of low-lying buildings and infrastructure to inundation and storm surges (Glavovic et al., 2022).

The projected intensification of these hazards introduces additional challenges for the built environment. Under the SSP5-8.5 scenario, substantial changes in the magnitude and frequency of climate extremes are projected (Almazroui et al., 2021). A recent global assessment (Sadati et al., 2026) of urban exposure to heatwaves, droughts and floods highlights the potential for multiple climate hazards to affect the same locations, with overlapping exposure prominent in urban areas across Africa, Southeast Asia and South America. They also identified substantial increases in extremes by the end of the century, including the exceedance of wet-bulb temperature thresholds in more than 120 cities, with heat stress of these levels causing danger to human health and life. Sub-Saharan Africa, western Brazil and large parts of the Middle East are projected to experience some of the greatest changes in surface temperature extremes (Sherman et al., 2022). CMIP6 multimodel projections for 2051-2080 indicate that, under SSP5-8.5, the probability of a heat extreme exceeding the previous local record by at least two standard deviations could reach approximately 40-50% per year across the northern midlatitudes (Fischer et al., 2021). Such record-shattering events are particularly challenging because their magnitude may fall outside the range represented by historical observations and therefore outside the conditions upon which existing buildings and infrastructure have been developed.

Exposure to repeated or increasingly severe hazards can damage buildings and infrastructure, and increase requirements for repair, replacement and reconstruction. Where buildings are damaged or destroyed, the consequences extend beyond the loss of assets. Climate-related damage will accelerate the transformation of material stocks into waste, increasing demands on waste management systems and generating additional requirements for construction materials (Joint UNEP/OCHA Environment Unit, 2011). This is especially important in densely populated urban areas, where large quantities of material stocks are concentrated within areas that may be exposed to multiple hazards. Coastal and riverine cities, for instance, are particularly susceptible to flooding, which

can undermine the structural integrity of buildings and necessitate large-scale rebuilding or relocation (OECD, 2019). Proactive adaptation measures such as managed retreat, strategically relocating communities from high-risk areas, are increasingly being recognised as essential components of climate resilience (Hino et al., 2017). Managed retreat also aligns well with circular economy goals. Rather than allowing buildings to be destroyed by disaster events, planned deconstruction enables the recovery and reuse of valuable materials, thus reducing raw material extraction, waste generation and associated emissions (Zaman et al., 2018).

2.2 Building material stocks

Bottom-up approaches estimate stocks by compiling data from individual buildings and infrastructure assets using physical attributes, such as floor area, construction year and typology, combined with material intensity coefficients (Lichtensteiger and Baccini, 2008; Tanikawa and Hashimoto, 2009). Bottom-up models are often more accurate and spatially explicit, making them suitable for high-resolution local assessments, including risk evaluation, and for supporting urban and regional planning, as emphasised by Lanau, Liu, et al. (2019). However, they are data-intensive and often constrained by data availability necessary for input. The application of geographic information system (GIS) technologies enhanced the spatial resolution of bottom-up models. Introduced into the field by Tanikawa and Hashimoto (2009), GIS has since become a standard tool in material stock research (Kleemann et al., 2017; Honic et al., 2023). By enabling the integration of georeferenced data, such as building location, size, age and type, with material intensity values, GIS-based MSA facilitates high-resolution urban and regional stock mapping. there has been a growing number of more refined, high-resolution local studies, improving estimates of embodied carbon and circular potential of material stocks in various locations (Lanau and Liu, 2020; Mao et al., 2020; Mollaei et al., 2021).

The methodology of MSA further advanced through the integration of remote sensing technologies, such as nighttime light (NTL) data (Takahashi et al., 2010; Peled and Fishman, 2021) and satellite imagery (Haberl et al., 2021). NTL data, derived from sensors that capture artificial illumination at night, have been used as proxies for human activity (Stokes et al., 2021) and urbanisation processes (Zhou et al., 2018). Although NTL data does not directly quantify material stocks, its strong correlation with urban development patterns makes it a valuable tool for identifying areas of built environment expansion, particularly in regions lacking detailed statistical or cadastral data. NTL data are especially useful for large-scale MSA and can serve as a complementary input to other methods. More recent developments in satellite imagery have enabled large-scale assessments of

building footprints, heights and volumes, which are vital inputs for quantifying material stocks with better accuracy. High-resolution datasets such as the Global Human Settlement Layer (European Commission, 2025) and the World Settlement Footprint (Earth Observation Center, 2025) provide globally consistent spatial coverage and have been used to derive material stock estimates and distribution, when combined with material intensity coefficients. An example of this work is outlined in the paper by H. Haberl et al. (2025), who estimated and mapped global building material stocks at a spatial resolution of 90 meters, by integrating data from the World Settlement Footprint with harmonised material intensity factors (Heeren and Fishman, 2019). This study classified five building types and 18 material categories, allowing not only improved material stock estimates but also unprecedented spatial and typological disaggregation (H. Haberl et al., 2025). Haberl and colleagues have created open-access, high-resolution data products, suitable for identifying spatial inequalities, localising urban mining potential and assessing climate impacts. The validation against case studies and the inclusion of the uncertainty analysis highlight the reliability of the dataset for the application in further studies.

3 Methods

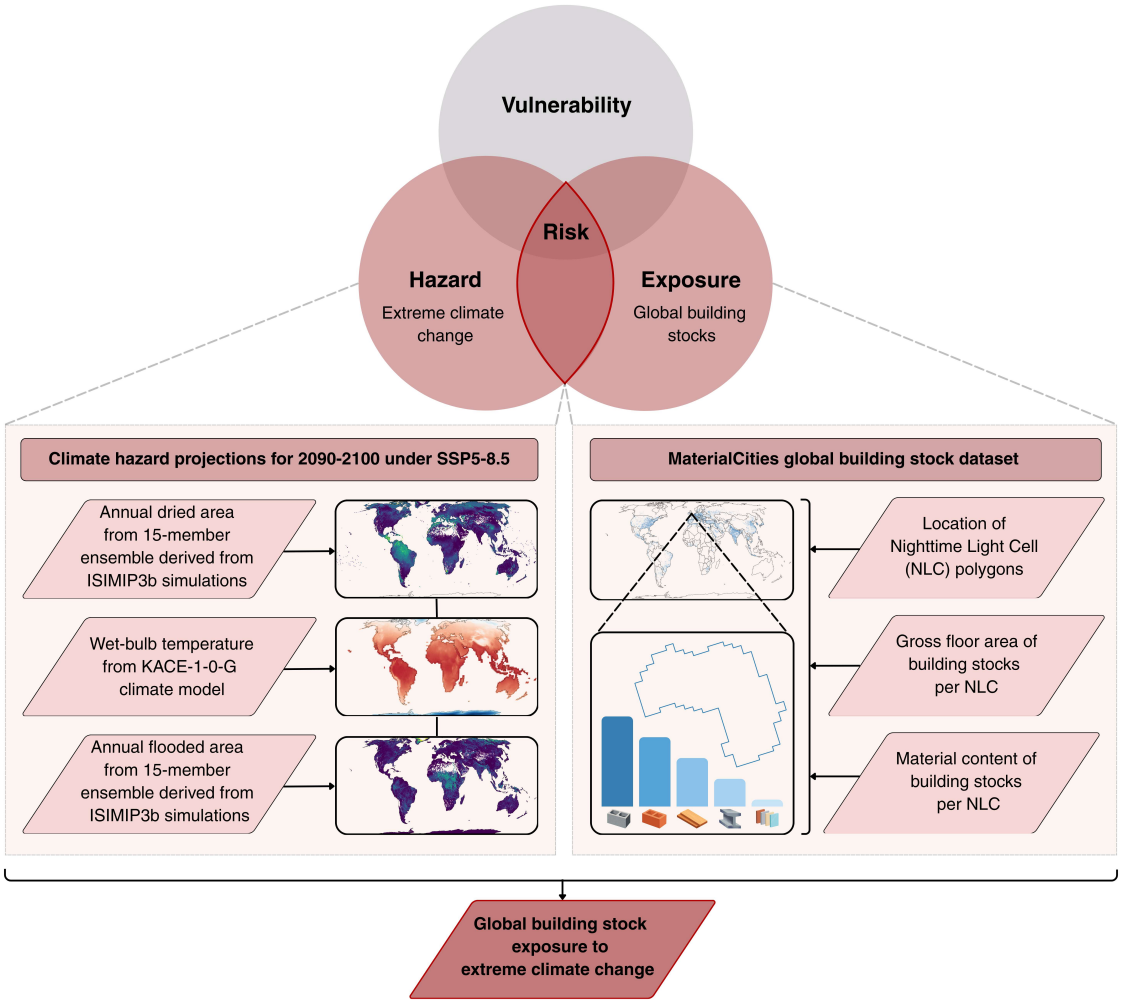


Figure 1: Methodological framework for assessing global building stock exposure to climate hazards.

To ensure a comprehensive climate change risk assessment, a risk triangle framework developed by Crichton (1999) is commonly utilised, including its use in the IPCC report on climate change impacts, adaptation and vulnerability (IPCC, 2014). The risk triangle is a conceptual model that highlights the interaction between the hazard, exposure and vulnerability, as shown at the top of Figure 1, providing an explanation to different levels of disruption and destruction caused by extreme climate and weather events in different contexts. It emphasises that disasters with their varying impact on communities, settlements and their built environment result from decisions about where and how people build, and how they address inequalities (Wisner et al., 2004). This framework also reflects the dynamic nature of disaster risk in the same location over time, as it can grow or decrease due to fluctuations in any of the three aspects forming the triangle.

3.1 Climate Hazard Data Preprocessing

The potential exposure of global building stocks to future climate hazards was assessed for three hazard categories: extreme heat, drought and fluvial flooding, as outlined in Figure 1. The analysis focused on the end-of-century period (2090-2100) under the high-emissions SSP5-8.5 climate scenario.

Extreme heat was represented using daily Wet-Bulb Temperature (WBT) projections from the bias-adjusted KACE-1-0-G climate model (Sandstad et al., 2021), available through the Copernicus Climate Change Service. The WBT dataset has a spatial resolution of 1.875° longitude × 1.25° latitude. Daily WBT values were analysed to quantify the frequency of extreme heat conditions by identifying days where WBT exceeded 35°C, a threshold used for human survivability. Annual exceedance was calculated for each grid cell and averaged across the 2090-2100 period to produce the mean annual quantity of extreme heat days. Additionally, this value was expressed as a proportion of the year, ranging from 0 to 1.

Drought and fluvial flood hazard projections were obtained from the Extreme Event Exposure Data for Drought and River Flood (v1.0) dataset (Heinicke et al., 2026), available through the ISIMIP Repository. The dataset provides hazard projections at a spatial resolution of 0.5° longitude × 0.5° latitude and is derived from simulations conducted within the Intersectoral Impact Model Intercomparison Project Phase 3b (ISIMIP3b). Both drought and fluvial flood analyses were based on a 15-member ensemble generated from combinations of three global hydrological models (H08, JULES-W2 and WaterGAP2.2e) and five CMIP6 climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL). The drought exposure analysis within this study implemented the annual dried area variable, while the flood exposure analysis utilised the annual flooded area variable, both ranging from 0 to 1 as proportions of each grid cell area exposed to separate hazards. For each ensemble member, annual hazard values were averaged over the 2090-2100 period. The ensemble mean hazard layers were subsequently generated by averaging across all 15 model combinations, reducing uncertainty associated with individual climate and hydrological model projections.

3.2 Integration with Building Stock Data

Following the preprocessing of climate hazard metrics, they were further integrated with the MaterialCities global building stock dataset (Fishman, Peled, et al., 2026), currently published as a preprint. MaterialCities provides spatially explicit estimates of gross floor area (GFA) and in-use building material stocks at high spatial resolution,

differentiated by three building functions and five load-bearing structural types using region-specific construction archetypes. The dataset includes estimates of eight major construction materials: concrete, brick, wood, steel, glass, plastics, aluminium and copper. The data are available across several spatial aggregation levels, from settlements to global regions.

Each climate hazard was converted into a point-based spatial dataset, where individual points represented climate model grid cells containing the corresponding hazard value. To restrict the analysis to terrestrial regions, ocean grid cells were removed where applicable. Both hazard points and the MaterialCities building stock polygons were projected into a common coordinate reference system (EPSG:3857) to enable accurate spatial distance calculations.

A nearest-neighbour spatial join was then applied to assign each building stock polygon the hazard value from its closest climate model grid cell. This approach enabled the transfer of gridded climate hazard information to the building stock dataset. The resulting datasets were subsequently transformed back to EPSG:4326 for subsequent analysis and mapping.

3.3 Building Stock Exposure

The total building stock for each spatial unit was calculated by adding all available material categories across all building archetypes. Two exposure indicators were calculated for each hazard.

The first metric represents the absolute quantity of building stock exposed:

$$E = M \times H \tag{1}$$

Where M is the total building stock and H represents the corresponding climate hazard metric:

- Proportion of days per annum with WBT ≥ 35°C;
- Proportion of dried area;
- Proportion of flooded area.

Additionally, to account for differences in building density and scale of the built

environment, a normalised exposure index was calculated:

$$E_{norm} = (\frac{M}{GFA}) \times H \tag{2}$$

Where GFA is the gross floor area of building stocks. As previously, M is the total building stock and H is the climate hazard metric. This index expresses hazard exposure relative to building material intensity, allowing comparison between countries and regions.

Exposure metrics were aggregated at the national level by adding E and E_{norm} values across all building stock polygons within each country boundary. Countries were ranked according to cumulative exposure for each hazard type to identify hot spots on the global scale.

4 Results and Discussion

4.1 Single-Hazard Building Stock Exposure

The single-hazard assessment reveals spatial variability in the exposure of global building stocks to extreme heat, riverine flooding and drought under the SSP5-8.5 scenario during the end of the century (2090–2100), as can be seen in Figure 2b, c and d.

The highest building stock exposure to extreme heat (Figure 2b), defined as the average annual occurrence of days with WBT ≥ 35°C, occurs throughout South Asia, particularly across northern and central India, Bangladesh and parts of Pakistan, where extensive building stocks coincide with a high frequency of extreme heat days. Southeast Asia also exhibits widespread exposure, with notable concentrations across Thailand, Vietnam and neighbouring countries. Outside of Asia, significant exposure is evident across parts of the United States, particularly along the Gulf Coast and southeastern states. Elevated exposure is also projected across parts of eastern China. In South America, building stock exposure is concentrated primarily within the more densely developed regions of eastern and southern Brazil, while lower exposure characterises much of the Amazon Basin. Comparatively limited exposure is observed across Australia, southern Africa and large parts of the Middle East. The countries identified among the ten most exposed are predominantly located within Asia and the Americas, reflecting the combined influence of high material stocks and frequent extreme heat occurrence. The heightened exposure within these regions suggests that future increases in extreme heat will disproportionately affect countries possessing both large populations and extensive urbanisation.

The building stock exposure to fluvial flooding (Figure 2c) is concentrated across South Asia, where dense settlements are located within flood-prone river basins. Northern India and Bangladesh exhibit particularly high exposure, consistent with the presence of large populations situated within the Ganges-Brahmaputra river system. Similar patterns are observed throughout parts of eastern China and mainland Southeast Asia. North America displays extensive exposure across the eastern United States, particularly within regions associated with the Mississippi River basin and adjacent urbanised areas. Western and central Europe also exhibit widespread building stock exposure, reflecting the concentration of built environment alongside major river networks including the Rhine and Thames. In Africa, Egypt is found to place itself among ten countries with the largest amounts of exposed stocks globally - an exception to the rest of the continent, despite the high flooded land area projections in surrounding countries with sparse settlements. Building stocks projected to be subjected to flooding are concentrated along the Nile River and Nile Delta. Relatively low exposure is also evident across Australia and central South America. While these regions contain localised areas of flood hazard, comparatively limited building stock density results in lower overall exposure within the global assessment. The countries identified among the ten most exposed are within Asia and the Americas, similar to extreme heat exposure results.

The global distribution of drought exposure (Figure 2d) exhibits a different spatial pattern from both extreme heat and riverine flooding. South and Central Europe exhibit widespread moderate to high building stock exposure to drought, extending across Portugal, Spain, Italy, Türkiye and the Balkans. The extensive distribution of urban centres throughout Europe contributes to elevated exposure. High levels of exposure are also observed in North Africa along the Mediterranean coastline and the Nile Delta in Egypt, compared to the rest of the continent. Additionally, heightened building stock exposure is concentrated in Latin America, with Mexico and Brazil highlighted among the most affected countries. In North America, moderate exposure is observed across the eastern United States. Similarly, Southeast and East Asia are characterised by moderate levels of drought impact, specifically across South Korea, Japan, Thailand, Indonesia, Malaysia and Vietnam. The ten most exposed countries maintain their distribution across Asia and the Americas, with the addition of Europe.

Despite the outlined differences, several geographic hot spots consistently emerge across all hazard assessments. These results establish a baseline understanding of hazard-specific building stock exposure globally and provide the foundation for subsequent comparison of multi-hazard impacts.

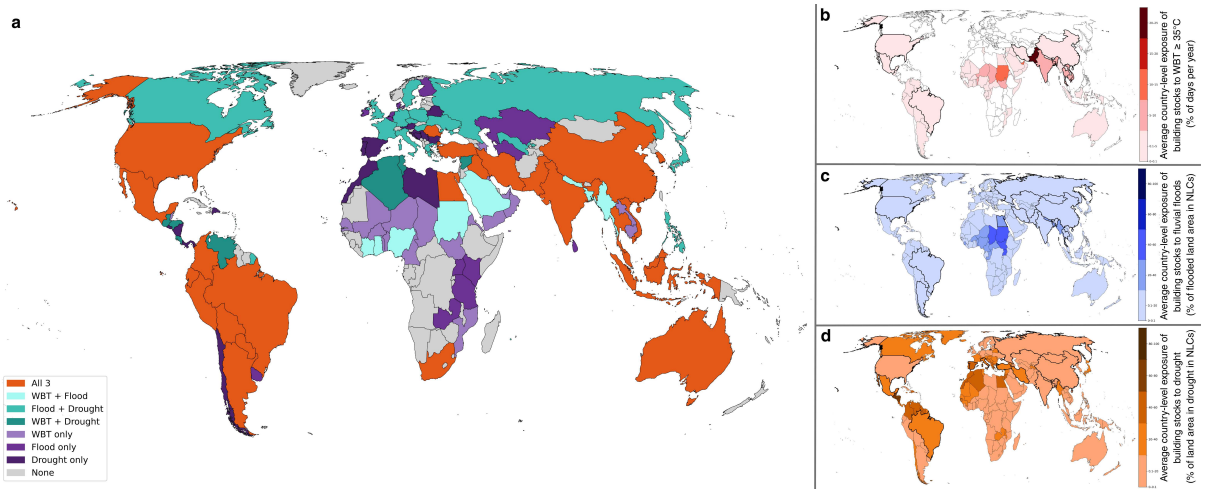


Figure 2: Global distribution of building stock exposure to extreme heat, fluvial flooding and drought. (a) National classification of building stock exposure according to the highest intensity of single hazards and all combinations of them. 75th percentile threshold implemented for extreme heat, flooding and drought exposure separately. (b-d) Global maps showing average country-level building stock exposure to (b) extreme heat, expressed as the percentage of days per year with WBT ≥ 35°C; (c) fluvial flooding, expressed as the percentage of land area in all within-country NLCs projected to be flooded; (d) drought, expressed as the percentage of land area in all within-country NLCs projected to be in drought. All hazard projections were obtained for 2090-2100, under SSP5-8.5. Top-10 countries with the most exposed stocks are outlined with thicker black borders.

4.2 Multi-Hazard Building Stock Exposure

The multi-hazard assessment identifies regions where global building stocks are simultaneously exposed to extreme heat, drought and fluvial flooding, in any combinations of them, under the SSP5-8.5 scenario during the same end-of-century period. Combining three hazard layers reveals several hot spots where multiple climate extremes would impact building stocks. These regions represent areas where buildings and populations may experience compound climate pressures, increasing the potential challenges for resilience and long-term adaptation.

The global mapping of building stock exposure with the 75th percentile threshold displays countries that are part of single, double and triple-hazard categories, as showcased in Figure 2a. The findings highlight South, East and Southeast Asia, Australia, South America and the United States, alongside a few nations in North and South Africa and the Middle East, as priority regions for climate adaptation, with their building stocks projected to be exposed to all three investigated hazards. These patterns are consistent with

the single-hazard results, which identified substantial exposure across parts of Asia and the Americas, while also highlighting the additional significance of overlapping hazards. The concentration of varied exposure across the regions identified suggests that future adaptation strategies should consider the cumulative effects of the hazards rather than address them independently. The combination of flood and drought dominated exposure stretches across high-latitude northern regions, including Canada, Russia, northern and central Europe. Highest exposure to extreme heat and drought appears in northern South America and nations of North Africa. Meanwhile, heightened impacts of extreme heat combined with flooding are projected to affect Saudi Arabia, Sudan, Nigeria, Ghana, Côte d'Ivoire, Bangladesh, Myanmar and Nepal. Several regions (e.g. central Africa, Oceania, parts of Central Asia, Baltic States, some of Central America and Caribbean) display lower projected exposure of their building stocks across all three severe weather events, placed below the 75th percentile threshold. However, these areas should not be interpreted as free from climate-related pressures.

The country-level analysis showcases the sub-national heterogeneity of exposure, as can be seen in Figure 3. In comparison to India's widespread high-level building stock exposure to all hazards, extreme heat exposure in the United States and China is comparatively restricted. Exposure to fluvial flood and drought in the US extends across the country, while it is limited to eastern regions in China. Countries, such as China and the US, account for greater absolute quantities of exposed materials, while smaller-stock nations, such as Pakistan, have the majority of their built-up areas (2.3 Gt or 56% of the national building stock) concentrated in locations experiencing more persistent extreme heat (20-40% of days per year), as illustrated by Figure 3d and e. The distinction between the potential scale of material exposure and the frequency of the associated hazard is significant when considering adaptation priorities. Meanwhile in Guatemala, 70% of their building stocks are projected to be located within areas facing drought. In Sudan, 44% of total stock will be exposed to riverine flooding. In this scenario, both countries would face severe consequences of climate change, particularly in settlements with low levels of resilience and adaptive capacity across physical and social infrastructure.

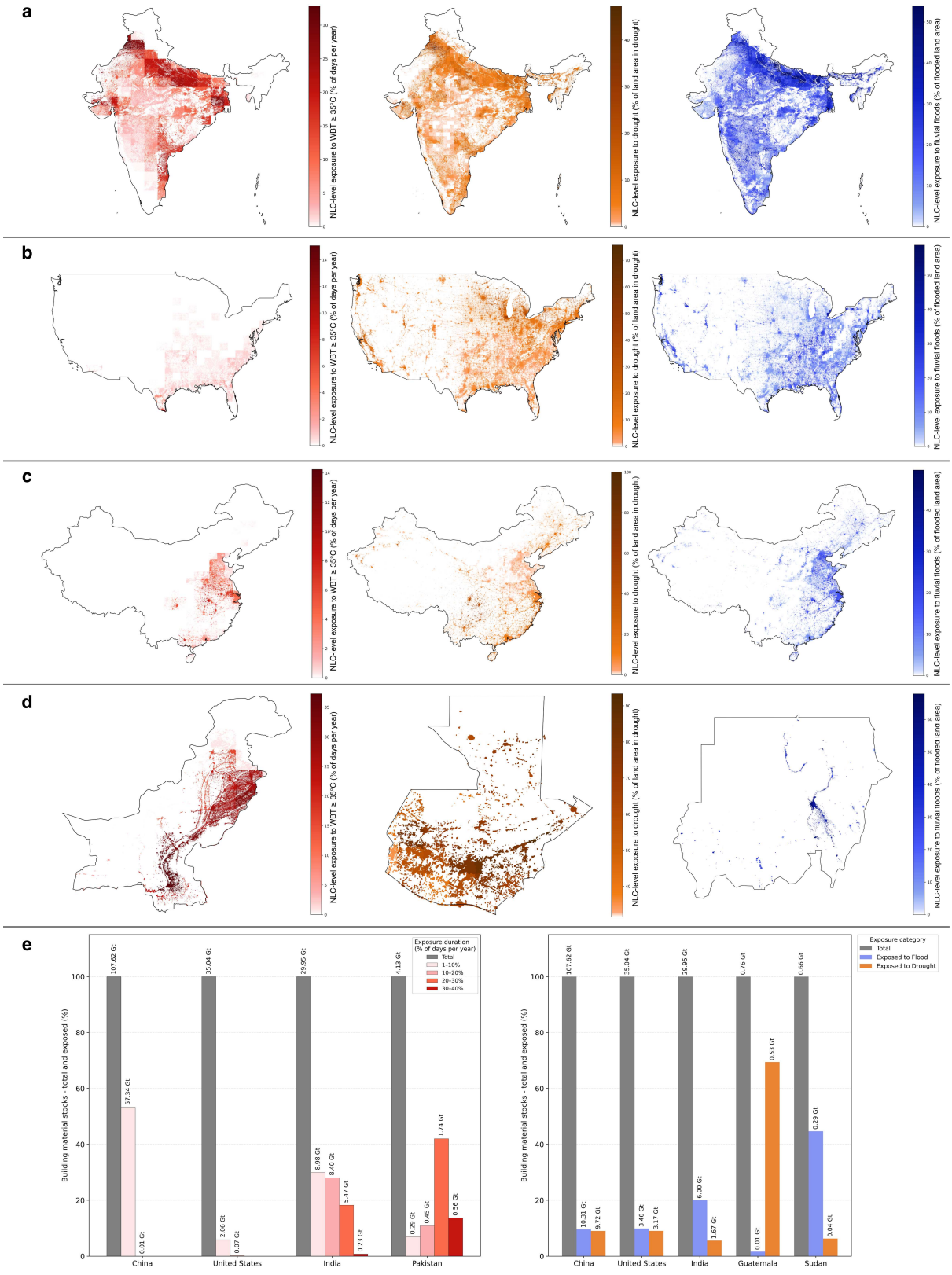


Figure 3: (Caption on the next page.)

Figure 3: (Previous page.) Spatial distribution and magnitude of building stocks exposure to extreme heat, drought and fluvial flooding across selected countries. (a-d) Spatial distribution of building stock exposure to extreme heat (left), drought (centre) and fluvial flooding (right) across (a) India, (b) United States, (c) China and (d) Pakistan, Guatemala and Sudan. Exposure is mapped at the NLC level. Countries chosen based on their national averages of hazards surpassing the global 75th percentile threshold. e) Comparison of total building stocks and exposed material stocks across selected countries. The left normalised bar chart shows the distribution of national-scale material quantities by duration of extreme heat exposure. The normalised bar chart on the right shows country-level material quantities exposed to fluvial flooding and drought. All values above the bars are in gigatonnes (Gt).

4.3 Material-Specific Exposure

The distribution of heat-exposed stocks globally is dominated by materials facing 1-10% of days per year exceeding the WBT of 35°C, led by 56 Gt of concrete and 23 Gt of brick, as shown on the bar chart on the left in Figure 4a. Exposed quantities decline across the higher extreme heat duration categories. However, shorter exposure may still have significant implications for populations and local infrastructure, increasing the overall risk that building stocks would be faced with. Following the amounts of heat exposure, all material groups are more exposed to drought than fluvial flooding, with quantities outlined on the right side of Figure 4a.

The amounts of specific materials exposed in each of the categories most impacted by different combinations of hazards can be seen in Figure 4b. The composition of these material stocks shapes how different climate hazards impact the built environments, demanding targeted adaptation approaches depending on whether a region faces fluvial flooding, extreme heat or drought. The analysis reveals that concrete and brick consistently form the vast majority (over 90% combined) of exposed material shares across both single-hazard and multi-hazard combinations. The prevalence of concrete as the main construction material is generally due to its availability, cost-effectiveness and structural performance. Its high thermal mass, however, makes it particularly susceptible to heat accumulation, particularly in countries exposed to severe thermal stress like the UAE, Venezuela and Bangladesh, leading to increased indoor temperatures and thermal discomfort in buildings, especially with exposed concrete on interior surfaces and without implementation of adequate cooling strategies (The Concrete Centre, 2025). Similarly to concrete, brick structures absorb and retain heat, therefore, both materials also contribute to the urban heat island effect in dense settlements (Wonorahardjo et al., 2020), further exacerbating the impacts of heat that cities are projected to experience. Prolonged and repeated inundation, possible in flood-prone nations such as Bangladesh, Russia and Kazakhstan, introduces degradation and failure risks for the dominant concrete-frame

building stock, generated by hydrostatic or hydrodynamic forces, impact of debris and local soil scour (Nadal et al., 2010). In drought-affected countries such as Spain, Russia and Venezuela, the primary structural threat stems from soil subsidence and potential subsequent heave when moisture is reintroduced into the ground, particularly in clay soils (Corti et al., 2009; Jones and Jefferson, 2012). High proportions of exposed building stock in these territories, especially consisting of masonry, could be facing settlement and damage in the form of cracking of structural elements, as shown in the case study undertaken in the Netherlands (Nicodemo et al., 2020).

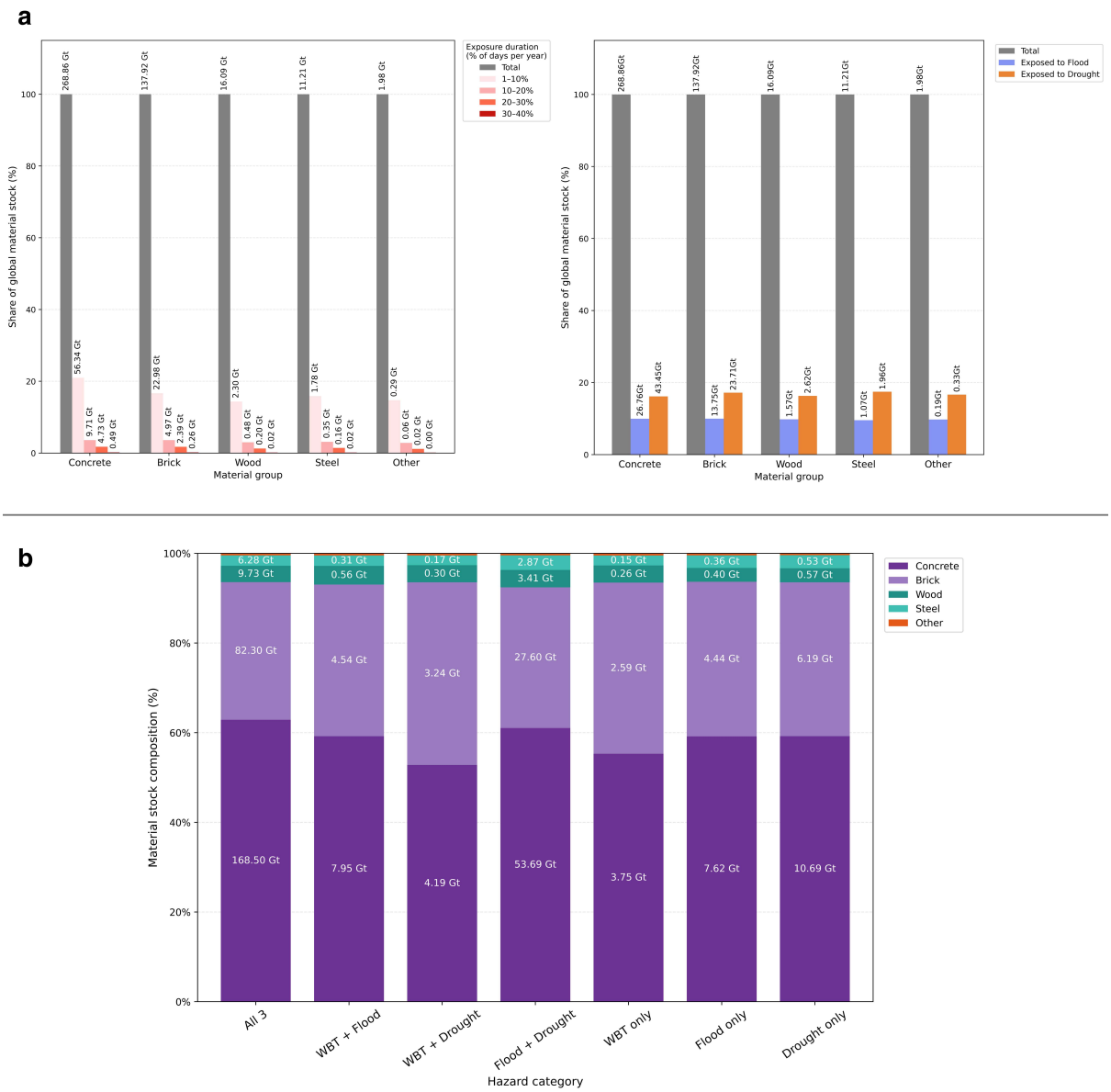


Figure 4: Exposure across material groups and hazard categories. (a) The normalised bar chart on the left shows quantities of concrete, brick, wood, steel and other materials exposed to extreme heat of varying duration across the year. The normalised bar chart on the right shows exposure of the same material groups to fluvial flooding and drought. (b) The normalised bar chart shows material composition of building stocks across the combined and individual hazard categories, which include countries where these hazards exceed the global 75th percentile threshold. All values above (a) and inside (b) the bars are in gigatonnes (Gt).

4.4 Implications

The distribution, quantity and composition of exposed material stocks provide an additional measure through which the consequences of climate hazards can be evaluated, adding to existing global assessments focused on climate change impacts on ecosystems and populations or economic losses from disasters (Intergovernmental Panel On Climate Change, 2023; United Nations Office for Disaster Risk Reduction, 2022; World Meteorological Organization, 2024; United Nations Office for Disaster Risk Reduction, 2025). Regions where large quantities of materials are exposed to multiple hazards may face greater challenges in maintaining housing, infrastructure and economic activity. However, material exposure is not a direct measure of climate risk, as the impacts of exposure are dependent on vulnerability factors, such as socioeconomic conditions and adaptive capacity. Meanwhile repeated exposure can further exacerbate social inequalities and amplify disaster risk, as seen, for instance, across informal settlements and low-income neighbourhoods within the urbanising Africa (D. Dodman et al., 2017).

Given the longevity of building lifespans and the substantial embodied carbon contained within construction materials, investing in proactive, targeted adaptation to protect existing building stocks would provide environmental and economic co-benefits compared with reactive large-scale reconstruction following damage from severe weather events (Rising et al., 2026). The exposure patterns identified in this study on the global scale reinforce the need for international cooperation in climate adaptation, particularly as many countries with the greatest projected exposure are rapidly urbanising and may face constraints in the financial and technical capacity required to implement large-scale resilience measures (Kapucu et al., 2024). Integrating building stock exposure into climate risk assessments and adaptation investment decisions could improve the allocation of international climate finance by identifying regions where interventions could protect substantial quantities of existing assets, while also making society more prosperous and raising the quality of life (Hallegatte et al., 2019). Considering material stock exposure alongside traditional economic indicators would therefore support more targeted and equitable distribution of adaptation resources.

While adaptation can reduce climate risks, persistent exposure to multiple severe hazards may eventually place limits on the effectiveness or feasibility of continued protection (Berkhout and Dow, 2023). In such circumstances, prospective analysis of building stock exposure could contribute to decisions concerning planned relocation. Managed retreat, as examined by Doberstein et al. (2020) and Lawrence et al. (2020), offers a proactive climate change adaptation (CCA) and disaster risk reduction (DRR) strategy by relocating communities and infrastructure away from high-risk zones. While most applications

of this strategy have been reactive, triggered by extreme events, the studies advocate for a forward-looking strategic planning approach embedded within national development agendas. The integration of managed retreat within material stock assessments offers a new avenue for urban mining, viewing exposed building stocks as potential sources of secondary construction materials, thus contributing to a circular economy. Planned deconstruction, rather than uncontrolled destruction caused by disaster events, would enable the recovery and reuse of materials in new places of residence post-migration, reducing raw material extraction, waste generation and associated environmental impacts (Pauliuk and Müller, 2014; Zaman et al., 2018). While this study does not quantify recoverable materials, its results provide a basis for future assessments of how exposed stocks could be protected, or salvaged and relocated.

4.5 Limitations

Several limitations should be considered when interpreting the results of this study. Firstly, although the MaterialCities dataset provides global coverage of building stocks, it is based on archetypes and available national and regional data (Fishman, Peled, et al., 2026). Consequently, it may underestimate or misrepresent building stocks in rapidly urbanising areas, informal settlements and regions where reliable data are limited, particularly across low-income countries. As informal housing often exhibits greater vulnerability to climate hazards, the exposure estimates presented here may underestimate risk in these locations. Additionally, the method developed in this study does not incorporate future urban expansion and building stock growth. As a result, the projected exposure represents the interaction between future climate hazards and currently in-use buildings stocks, providing baseline exposure figures and spatial patterns.

Secondly, uncertainty arises from the climate projections. Although the drought and flood hazards were derived from a 15-member climate-hydrological ensemble, reducing uncertainty associated with individual models, the extreme heat assessment relied on a single climate model and does not represent the full range of inter-model variability. Furthermore, uncertainty in regional climate projections increases towards the end of the century, particularly for precipitation-related hazards, meaning that the magnitude of projected exposure should be interpreted with caution. Nevertheless, the identification of hot spots remains valuable for estimating long-term impacts and adaptation planning (Ranasinghe et al., 2023).

Thirdly, the spatial resolution of the climate hazard datasets introduces uncertainty into the exposure assessment. The extreme heat dataset has a relatively coarse resolution ($1.875^\circ \times 1.25^\circ$), while the drought and fluvial flood datasets are available at 0.5°

resolution. Assigning hazard values to building stock polygons using a nearest-neighbour spatial join assumes that each building stock datapoint is subjected to the conditions represented by the nearest coarse climate model grid cell. Although appropriate for a global-scale assessment, this approach does not capture local climatic variability and the subsequent impacts on non-aggregated stocks.

Additionally, the representation of extreme heat using the annual frequency of days exceeding the WBT threshold of 35°C acts as a simplified proxy for heat-related exposure. Although this threshold is widely recognised as a physiological limit for human survivability (Sherwood and Huber, 2010), heat impacts on populations are influenced by factors such as acclimatisation, demographic characteristics and access to cooling. Consequently, the selected threshold is effective for identifying regions exposed to extreme thermal conditions but may underestimate exposure to lower-intensity heat events that still produce substantial impacts on human health.

Similarly, drought and fluvial flooding were represented using the proportion of grid cell area affected by each hazard, rather than hazard intensity or duration. While these metrics provide a consistent basis for global comparison, they do not capture characteristics such as flood depth, drought severity or event recurrence, all of which strongly influence the magnitude of impacts. The exposure estimates presented here should therefore not be interpreted as estimates of physical damage and used with caution for any further analysis, such as quantification of projected economic losses.

Finally, this study focuses on physical exposure rather than overall climate risk. Although exposure is a key component of risk, impacts are also determined by vulnerability and adaptive capacity. Differences in building standards, implemented adaptation measures, economic development, sociodemographic characteristics and institutional capacity mean that countries with similar levels of exposed material stock may experience substantially different consequences. Future work could integrate aforementioned national-level indicators with building stock exposure to produce assessments of climate risk.

4.6 Conclusion

Climate change is creating increasing pressures on the built environment, with implications extending to the populations it accommodates, the activities it supports, and the material resources embedded within it. This study focuses on one dimension of risk - exposure of building stocks to climate hazards - to enable a better understanding of the challenges that the built environment is burdened to face. It provides the first global assessment of building material stocks exposed to extreme heat, fluvial flooding and drought

under extreme climate change, quantifying exposure across the single and multiple hazards, and several material groups. By identifying exposure hot spots on a global scale, the results provide a foundation for linking material stock analysis with climate change adaptation strategies on national and local scales, where they are actioned and are the most impactful.

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