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Exposure to Large Landslides in Cities Outpaces Urban Growth

Joaquin V. Ferrer[1,2], Cassiano Bastos Moroz[1], Selin Yüksel[1], Olivier Dewitte[3], Karen Lebek[1], Norbert Marwan[2], Jürgen Kurths[2], and Oliver Korup[1]

[1]Institute of Environmental Sciences and Geography, University of Potsdam, Potsdam-Golm, Germany, [2]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany, [3]Department of Earth Sciences, Royal Museum for Central Africa, Tervuren, Belgium

Key Points:

- We identify 1,085 large (>0.1 km^2) urban landslides inhabited by half a million people in total
- Built-up areas on large landslides have doubled from 1985 to 2015
- Population trends of adjacent mountain regions raise landslide exposure across 129 cities

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

J. V. Ferrer,
ferrer@uni-potsdam.de

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Author Contributions:

Conceptualization: Joaquin V. Ferrer, Norbert Marwan, Oliver Korup
Data curation: Joaquin V. Ferrer, Selin Yüksel, Olivier Dewitte
Formal analysis: Joaquin V. Ferrer, Oliver Korup
Funding acquisition: Norbert Marwan, Jürgen Kurths, Oliver Korup
Investigation: Joaquin V. Ferrer, Cassiano Bastos Moroz, Selin Yüksel, Olivier Dewitte, Norbert Marwan, Oliver Korup
Methodology: Joaquin V. Ferrer, Selin Yüksel, Oliver Korup
Project administration: Norbert Marwan, Jürgen Kurths, Oliver Korup
Resources: Joaquin V. Ferrer
Software: Joaquin V. Ferrer
Supervision: Norbert Marwan, Jürgen Kurths, Oliver Korup
Validation: Joaquin V. Ferrer, Cassiano Bastos Moroz, Selin Yüksel

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Abstract The world's rapidly growing urban population is forcing cities to expand into steeper terrain, increasing the risk of landslides. However, systemic assessments of urban landslide exposure are limited. Across 129 cities and their surrounding commuting areas, we identify 1,085 large (>0.1 km^2) landslides that are currently inhabited. Between 1985 and 2015, built-up areas on these landslides have doubled, exceeding the overall urban growth rate. We estimate that at least half a million people are living on landslides and have expanded their total built-up area by 12%, on average, over 30 years. Population trends in adjacent mountain regions increased landslide exposure, with 10% of cities showing disproportionately high exposure. Our study reveals that landslide exposure in mountainous areas around cities grew faster than in commuting areas, regardless of national income. Further model refinements with high-resolution land use data and socio-economic predictors can help quantify the impact of urban zoning policies on global landslide exposure.

Plain Language Summary As the global population grows, more people are moving to steep slopes around cities, increasing their exposure to large landslides. We investigated the growth of permanent structures of human settlements from 1985 to 2015 on 1,085 large (>0.1 km^2) landslides. Across 129 cities, we find that the built-up areas on these landslides has doubled over 30 years, growing faster than the cities themselves. We estimate that at least half a million people live on these large landslides. Our study finds growth of permanent structures on large landslides is driven more by people moving from mountain areas to cities than by urban expansion. We observe that informal settlements on steep slopes with landslides are likely putting vulnerable populations at risk. Our model approach and findings can be used to inform urban zoning policies and reduce the exposure of marginalized urban communities to landslides.

1. Introduction

Approximately 39 million people are annually exposed to rainfall-triggered landslides alone (Emberson et al., 2020), marking widespread global exposure to this potentially destructive geomorphic hazard. While the bulk of landslide research has been concerned with identifying which terrain is most susceptible to slope failure in remote upland areas, fewer studies examine landslide exposure in population centers at comparable detail (Ferrer et al., 2024; Kühnl et al., 2022; Nieto et al., 2025). Cities across the world have expanded by 4% per year on average since 1990 (Behnisch et al., 2022), and urban areas could triple between 2015 and 2050 (Lwasa et al., 2022). However, any global overview that estimates commensurate urban landslide exposure remains elusive.

Mountain cities sprawling under population pressure are particularly affected by migration from rural to urban areas as people pursue economic opportunity, sometimes fleeing from conflict and environmental degradation (Bachmann et al., 2019; Ehrlich et al., 2021). These cities are likely facing both expanding populations and rising exposure to flood and landslide hazards in a changing climate (Adler et al., 2022). At present, a third of the people in mountains are living in cities, after a two-fold increase between 1975 and 2015 (Thornton et al., 2022). Many of these new urban developments extend to steeper hillslopes (K. Shi et al., 2023), and hence areas of higher landslide potential.

Similarly, coastal cities impacted by climate change could find urban neighborhoods densely built-up in frequently flooded areas (Rentschler et al., 2023) facing inundation from rising sea levels (Glavovic et al., 2022; Nicholls et al., 2021; Ohenhen et al., 2024; Oppenheimer et al., 2019). Consequently, parts of these cities also

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Visualization: Joaquin V. Ferrer, Cassiano Bastos Moroz, Karen Lebek
Writing – original draft: Joaquin V. Ferrer, Cassiano Bastos Moroz, Selin Yüksel, Olivier Dewitte, Karen Lebek, Norbert Marwan, Jürgen Kurths, Oliver Korup
Writing – review & editing: Joaquin V. Ferrer, Cassiano Bastos Moroz, Selin Yüksel, Olivier Dewitte, Karen Lebek, Norbert Marwan, Jürgen Kurths, Oliver Korup

expand to higher elevations (Hino et al., 2017; Pinter et al., 2019; Tamura et al., 2023) as people move away from flood-prone zones (Kimmelman & Haner, 2017; Mach et al., 2019; Setiadi et al., 2023; Siders, 2019).

By moving uphill, people have settled near, or even on, large landslides (Ferrer et al., 2024), defined here as affecting a total area of >0.1 km^2. These slope failures play a significant role in shaping hillslopes and river reaches (Hewitt et al., 2008; Korup et al., 2007; Marc et al., 2019; Moreiras & Sepúlveda, 2015) and can comprise multiple deposits of various, movement types, states of activity, and deformation rates (Bhuyan et al., 2024; Dille et al., 2019; Hungr et al., 2014). Communities located on such active, large landslides are exposed to damage from pervasive motion, and a high variance of instability and ground deformation (Maki Mateso et al., 2024; Mansour et al., 2011). Large landslides have in some cases also reactivated or culminated in catastrophic collapse, often—though not exclusively—triggered by earthquakes or rainstorms (Dille et al., 2019; Fan et al., 2019; Lacroix et al., 2020; Roberts et al., 2019; Seguí et al., 2020; Shan et al., 2023). In the event of an earthquake, locations on upper hillslope portions, where many crown areas of large landslides are situated, can experience peak ground accelerations up to three times that of the toe (Jibson & Harp, 2016). Hence, buildings on landslides are exposed to greater structural damage (Fotopoulou & Pitilakis, 2013, 2017) and a higher likelihood of collapse (Raj et al., 2024).

Most large landslides may appear quiescent, with movement too subtle to detect (Van Wyk de Vries et al., 2024), and an unknown state of activity or likelihood to reactivate (Ambrosi et al., 2018; Hasegawa et al., 2009). Urban development on landslides has reactivated (Notti et al., 2015) and accelerated slope deformation rates (Dille et al., 2022). Urban growth on steeper slopes will likely incur greater landslide risk (Ozturk et al., 2022; Rusk et al., 2022), as even a single large landslide in a densely populated urban area can cause numerous fatalities (Fidan et al., 2024; Gómez et al., 2023).

Hence, growing cities face an uncertain level of large landslide exposure on steeper slopes. Clearly, this exposure must be addressed locally, but also systematically, such as in the integrated climate adaptation policies of the upcoming IPCC *Special Report on Climate Change and Cities* (Prieur-Richard et al., 2019). Motivated by this uncertainty, we estimate the exposure to large landslides in metropolitan cities with >50,000 inhabitants, simply referred to as *cities* in the following. Here, we estimate exposure to large landslides from the spatial intersection of permanent building footprints and large landslide areas. We adapt this measure of exposure from a recent study concerned with the presence of human settlements on large, slow-moving landslides (Ferrer et al., 2024). We looked into the presence of built-up areas on large landslides with states of activity that have allowed human settlement, therefore excluding recent catastrophic slope failures. We examine the effect of shifting population trends from 1985 to 2015 on landslide exposure across these cities (Figure 1). To this extent, we model local and national trends in exposure in built-up areas on 1,085 large landslides across 129 cities and 11 countries (Methods: 2).

2. Data and Methods

2.1. Global Metropolitan Cities and Mountain Region Population Shifts

We focused on cities with >50,000 inhabitants by 2015, identified in the Global Human Settlement Layer's settlement model (GHS-SMOD) (Schiavina, Melchiorri, & Pesaresi, 2023). These *n* cities are defined by an urban center and the surrounding metropolitan regions comprising their greater commuting areas that capture areas of mobility into these urban centers (Moreno-Monroy et al., 2021). Expanding populations of these urban centers mean that built-up areas become part of, or transform into, metropolitan cities that grow into adjacent areas with communities with a greater commuting population and labor force. To estimate this effect, we used spatial data on *Functional Urban Areas* (GHS-FUA) (Moreno-Monroy et al., 2021; Schiavina et al., 2019) that outline these cities and their metropolitan regions, as of 2015. These data estimate the area around urban centers, in which at least 15% of residents commuted into the city, empirically derived from a model trained on metropolitan areas from 31 countries from within the European Union. This model was further calibrated according to urban density, level of infrastructure, and the geographical characteristics to mitigate possible bias from the country sample and to be applicable to developing countries. Thus, we focus on metropolitan cities with regions that include both greater commuting areas and urban centers, simply referred to as *cities* in the following.

Strong urbanization has accompanied population growth in mountain regions, with up to 40% of people now living in cities (Thornton et al., 2022). Urban population growth in mountain cities between 2000 and 2015 was

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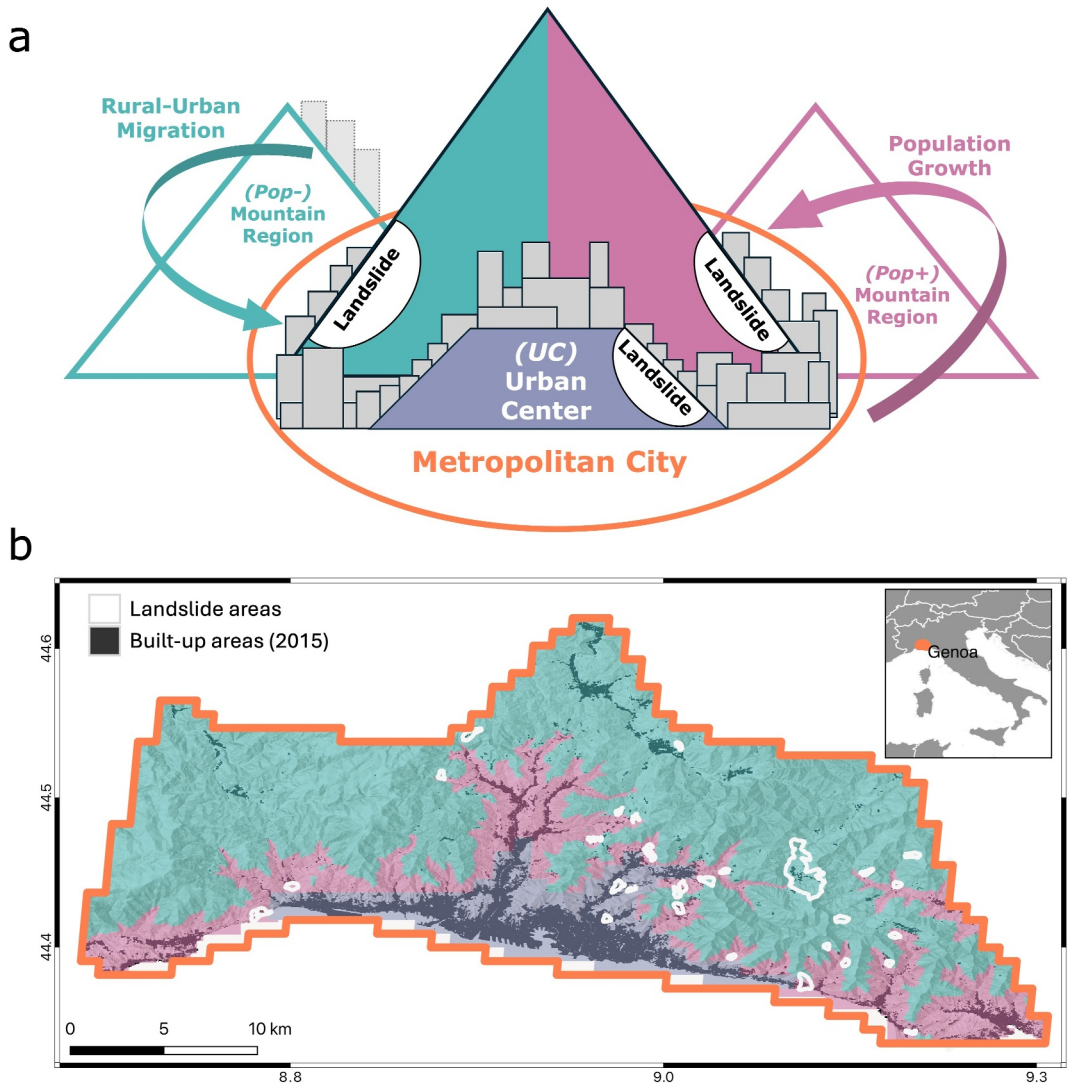

Figure 1. *Concept of landslide exposure in cities influenced by population trends*. (a) Growth of built-up areas (gray) in cities and their metropolitan region (orange outline) in and from urban centers (purple), interacts with changes in population dynamics in the surrounding mountains. Built-up areas grow outward from urban center into steeper terrain prone to landslides (white semi-circles). Urban development in mountains has had mostly growing populations (*Pop+*), either establishing more buildings (gray) that climb uphill from urban centers; or that are built to accommodate more people incoming from rural areas ((*Pop−*), light gray). (b) Case example of the concept in panel (a), showing built-up areas on landslides in the city of Genoa, Italy, in the same color codes. Data are from the Global Human Settlement Layer (Moreno-Monroy et al., 2021; Schiavina et al., 2019); mountain regions (Snethlage et al., 2022) with population trends (*Pop+* and *Pop−*) from Thornton et al. (2022); 2015 built-up areas (Marconcini et al., 2021); basemap is ESRI World Hillshade; insert map made with Natural Earth; All maps in panel (b) using QGIS V3.24.0.

generally higher than the total population increase across mountain areas (Bachmann et al., 2019). Migration from rural mountain areas to cities has widely contributed to this growth. Thus, we investigate the influence of both population pressure from growing mountain cities and migration from rural mountain areas around expanding cities. We used the Global Mountain Biodiversity Assessment (GMBA, version 2) (Snethlage et al., 2022) that contains a database of hierarchical and transparent delineations of mountain ranges worldwide. We used an assessment of the changes in population density across these GMBA mountain regions (Thornton et al., 2022), based on multi-temporal population gridded data from 1975 to 2015 from the Global Human Settlement Layer (GHS-POP) (Schiavina, Freire, et al., 2023). We derive insight from the population change data using this combination of data comprehensive efforts to compare different mountain categories and population change data sets (Thornton et al., 2022). Hence, we have more confidence in the representation of mountain regions from the

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GMBA and population trends from the GHS-POP data. We encoded these long-term regional population trends observed across GMBA mountain regions of this assessment and intersected these with the cities from the GHS-FUA, and labeled areas of population increases (decreases) as *Pop+* (*Pop−*) over this 40-year period. Hence, we obtained geospatial information on long-term regional population dynamics that could be influencing cities in our study.

2.2. Growing Built-Up Areas on Large Landslides

We focused on large landslides areas only, within cities and their surrounding commuting areas forming metropolitan regions (Figure 1), and refer to these slope failures simply as *landslides*. We compiled a database of 1,085 landslides located within cities (Ferrer, 2025) from 20 inventories in scientific publications (Dewitte et al., 2021; Dille et al., 2022; Fusco et al., 2023; Görüm, 2019; Handwerger et al., 2022; Mirus et al., 2020; Pánek et al., 2019; J. S. Shi et al., 2016; Tomás et al., 2014; Wartman et al., 2013; Xu et al., 2020; Xu, Liu-Zeng, et al., 2021; Xu, Schulz, et al., 2021); maps we digitized (Bourenane et al., 2016; Duman et al., 2005; Roberts et al., 2019); and openly accessible institutional databases (Dipartimento per il Servizio Geologico d'Italia, 2022; Franczyk et al., 2019; NIED Japan, 2015; PAI, n.d.; Serviço Geológico do Brasil, n.d.; Slaughter et al., 2017; Štátny geologický ústav, n.d.). We only considered landslide inventories following Findable, Accessible, Interoperable, and Reusable guiding principles. This database mostly consists of polygon outlines of reported total landslide footprint areas, mostly without distinction of source or deposit areas, or current state of activity.

In order to track the expansion of urban built-up areas on each of these landslides, we used high-resolution data on the growth of human settlements from 1985 to 2015, drawing on the World Settlement Footprint Evolution (WSF-Evo) (Marconcini et al., 2021). The WSF-Evo data used Landsat-5/7 Landsat imagery to outline yearly changes in global settlements at 30-m resolution, using 2015 as a reference year and going back to 1985 (Marconcini et al., 2020, 2021). The WSF-Evo data have shown annual average rates of settlement growth in a comparison study (Taubenböck et al., 2024), similar to those of the Global Human Settlement Layer Built-Up Grid (GHSL), which is an alternative multi-temporal data set on built-up presence derived from Landsat image collections (Schiavina, Melchiorri, & Pesaresi, 2023). These data allowed us to produce individual time series showing the rate of expansion of built-up areas for each landslide over 30 years.

We estimated the mean slope of each landslide in cities derived from Shuttle Radar Topography Mission digital elevation model (Farr & Kobrick, 2000) at a 1 arc second resolution and processed using Google Earth Engine (Gorelick et al., 2017). Similarly for each of the cities, we derived the mean slope and standard deviation across the corresponding urban centers and the mountain region. We also estimated the total population living on the documented landslides, and obtained a snapshot of the population within each landslide polygon in 2015 from a 100-m resolution global grid WorldPop data set (Lloyd et al., 2017; Tatem, 2017). Hence, we excluded this static exposure estimate as a possible predictor in our models.

2.3. Bayesian Multilevel Modeling

To learn from these data, we modeled the growth of built-up areas on landslides over 30 years both overall and at the level of different countries. Our target variable is the built-up areas on large landslides, and we approximate this exposure as the fraction of WSF-Evo settlement footprint area per reported landslide area. Although this approach may not capture all aspects of exposure exhaustively, it remains an objective, consistent, and global way of capturing exposure as a component of landslide risk. Moreover, the data layer on permanent structures that occupy large landslides also contains infrastructure such as roads and utilities.

While this percentage of occupied landslide area has values on the unit interval [0, 1], we observe that it is nearly 0% or 100% on many individual landslides reported. An unknown number of these zero cases may be prone to incomplete landslide reporting, whereas nearly completely built-on landslides may be over-represented. In other words, the 100% value refers to a fully occupied large landslide that still may only make up a minute fraction of the metropolitan area. To account for this effect in estimating trends in time, we used a zero-and-one-inflated beta regression (Ferrari & Cribari-Neto, 2004) in a Bayesian multi-level setup (Gelman, 2006; Gelman & Hill, 2006; McElreath, 2018).

The zero-and-one-inflated beta (BEINF) distribution mixes a Beta distribution with a Bernoulli distribution to account for excess zeros and ones (Ferrari & Cribari-Neto, 2004) in the data, and thus accommodates both

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proportional responses, (i.e., responses in percentages or ratios on unit scales), and those clustered at the extremes of zero and one. The BEINF distribution has been used in several natural hazard studies, ranging from wildfire occurrences (Ríos-Pena et al., 2018) to flood loss ratios (Schoppa et al., 2020). The BEINF cumulative distribution function (CDF) is:

$$\mathrm{BEINF}(y|\lambda,\gamma,\mu,\phi) = \lambda F_B(y|\gamma) + (1-\lambda)F_B(y|\mu,\phi) \tag{1}$$

where $y \in [0, 1]$ is the fraction of built-up area on landslides; $\lambda \in [0, 1]$ is the zero-and-one inflation probability; $F_B(y|\gamma)$ is the CDF of the Bernoulli distribution with the conditional one-inflation probability $\gamma \in [0, 1]$; and $F_B(y|\mu, \phi)$ is the CDF of the Beta distribution with mean $\mu \in (0, 1)$ and precision $\phi > 0$ (Ferrari & Cribari-Neto, 2004). We modeled the fraction of built-up landslide area as:

$$y_i \sim \mathrm{BEINF}(\lambda_i,\gamma_i,\mu_i,\phi_i) \tag{2}$$

where y_i is the fraction of built-up area on an ith landslide in a given city.

We use a multi-level Bayesian approach to estimate the effects of different groups in our data. A multi-level model offers a compromise between separate group-wise models limited by fewer data and a single pooled model that learns from all the data, though without distinction (Gelman & Hill, 2006; McElreath, 2018). Multi-level models cater to comparing between groups and the pooled tendency in a single setup. Assuming that both landslide and urban settlement data likely reflect many different physical and socioeconomic drivers, we obtained for each landslide its city and country as a nested group level. Given the diversity of the data sources for our catalog, it seems prudent to assume that the data also reflect differing protocols of mapping landslides at both city and national level. At the first level, we assigned to each landslide a country label. We further assigned to each landslide one of the three groups (*Pop+*, *Pop−*, or *UC*) to capture urban population trends: built-up landslides in cities impinging on mountainous terrain with population growth (or decline) are labeled *Pop+* (or *Pop−*), while landslides within urban centers are labeled *UC*.

The nested multi-level model reflects our hypothesis that mountain regions in the same country reflect similar land-use policies, or disaster risk reduction and mitigation efforts that may affect how landslide-prone terrain is being built on. Similar, national policies and socioeconomic environments may also influence whether and how people migrate from rural areas into urban centers or vice versa. Thus, each landslide i belongs to one of the $J \in \{1, \ldots, 3\}$ groups for urban population, and one of the $K \in \{1, \ldots, 11\}$ countries. We estimated the mean annual rate of the fraction of built-up areas on landslides, by using the calendar year T as a predictor. We use the logit link function to ensure that μ_i remains on the unit interval and use two bivariate Gaussian distributions to model the correlated coefficients of the linear predictor:

$$\mathrm{logit}(\mu_i) \sim \alpha_{j,k} + \beta_{j,k}T \tag{3}$$

$$\begin{pmatrix}\alpha_j\\ \beta_j\end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix}\mu_{\alpha_j}\\ \mu_{\beta_j}\end{pmatrix}, \begin{pmatrix}\sigma^2_{\alpha_j} & \rho_{\alpha_j\beta_j}\\ \rho_{\beta_j\alpha_j} & \sigma^2_{\beta_j}\end{pmatrix}\right), \text{ for each group } j = 1,\ldots,J \tag{4}$$

$$\begin{pmatrix}\alpha_k\\ \beta_k\end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix}\mu_{\alpha_k}\\ \mu_{\beta_k}\end{pmatrix}, \begin{pmatrix}\sigma^2_{\alpha_k} & \rho_{\alpha_k\beta_k}\\ \rho_{\beta_k\alpha_k} & \sigma^2_{\beta_k}\end{pmatrix}\right), \text{ for each group } k = 1,\ldots,K \tag{5}$$

We further specified the population-level effect of the calendar years T as a linear predictor for variance ϕ_i:

$$\log(\phi_i) \sim \alpha_0 + \beta_0 T \tag{6}$$

where α_0 and β_0 for variance ϕ are population-level coefficients.

A Bayesian approach requires a choice of priors. We used weakly informative priors for pooled intercepts and standard deviations of coefficients across groups by assigning half Student-t prior distributions centered around zero, with three degrees of freedom, and a standard deviation of 2.5, based on standardized data (Gelman, 2006).

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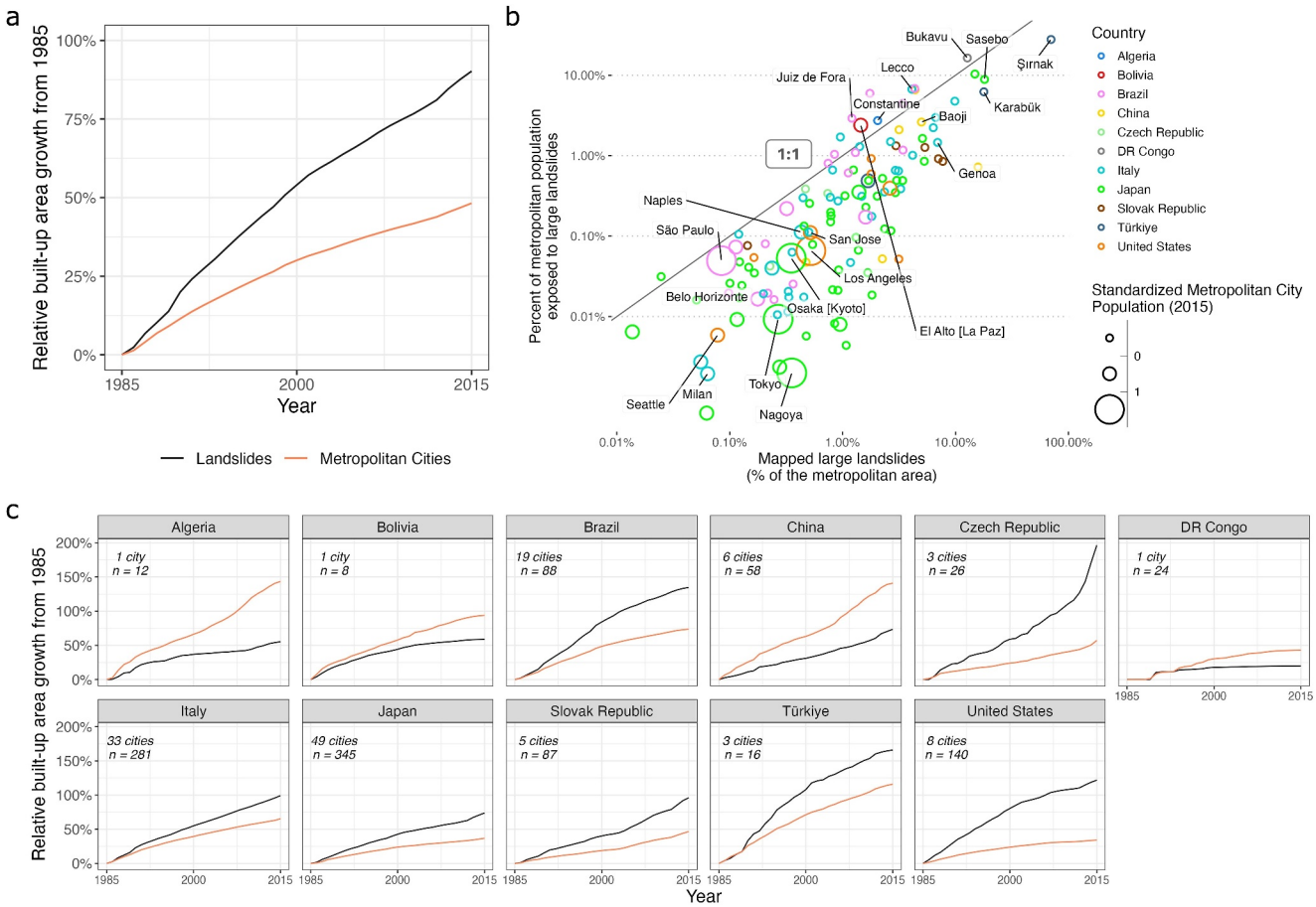

Figure 2. *Urban growth onto landslides exposes metropolitan populations*. Landslide exposure in cities showing (a) global overview of relative built-up area growth on landslides compared to the growth of cities, 1985–2015; (b) percentage of people exposed to large landslides in 2015 per metropolitan population and the relative fraction of area affected by known large landslides, solid gray line shows 1:1 ratio; bubble size is scaled to total 2015 population; and (c) relative built-up area growth on landslides and cities per country; *n* is number of reported landslides.

We chose a Lewandowski-Kurowicka-Joe (LKJ) Cholesky correlation distribution as a prior for group-level effects to express uniform density over correlation matrices (Bürkner, 2017). In modeling the response of the mean annual rate of the fraction of built-up areas on the landslides to calendar year, we used a flat prior to reflect the lack of prior knowledge and absence systemic information on the temporal trends of landslide exposure across cities (Gelman et al., 2017).

We numerically approximated the posterior distribution using a Hamiltonian Monte Carlo algorithm implemented in the probabilistic programming language STAN (S. D. Team, 2023), and a No-U-Turn Sampler (NUTS) within the software package *brms* (Bürkner, 2017) in the statistical computing environment **R** (R. C. Team, 2023).

3. Results

3.1. Exposure Nearly Doubles Across Cities

We find that the total built-up area on the 1,085 large landslides in cities nearly doubled (90% from 1985) over 30 years, and outpaced the overall rate of urban growth on average (48% from 1985, Figure 2a). We estimate that at least 536,000 people by 2015 are present and living on these large landslides, hosting a total of 1.95 billion residents (Figure 2b). This seemingly low proportion of people living on landslides betrays highly skewed distributions: 12 cities have more people per unit area on landslides than on stable land; 15 cities have >5% of their areas affected by landslides, and as high as 70% in Şırnak, Türkiye, followed by 18% in Sasebo, Japan. In at least eight countries, the growth rate of built-up areas on landslides surpassed that of the cities (Figure 2c). In Algeria, Bolivia, and DR Congo, growing built-up areas on landslides seem to have slowed down since 2000; however,

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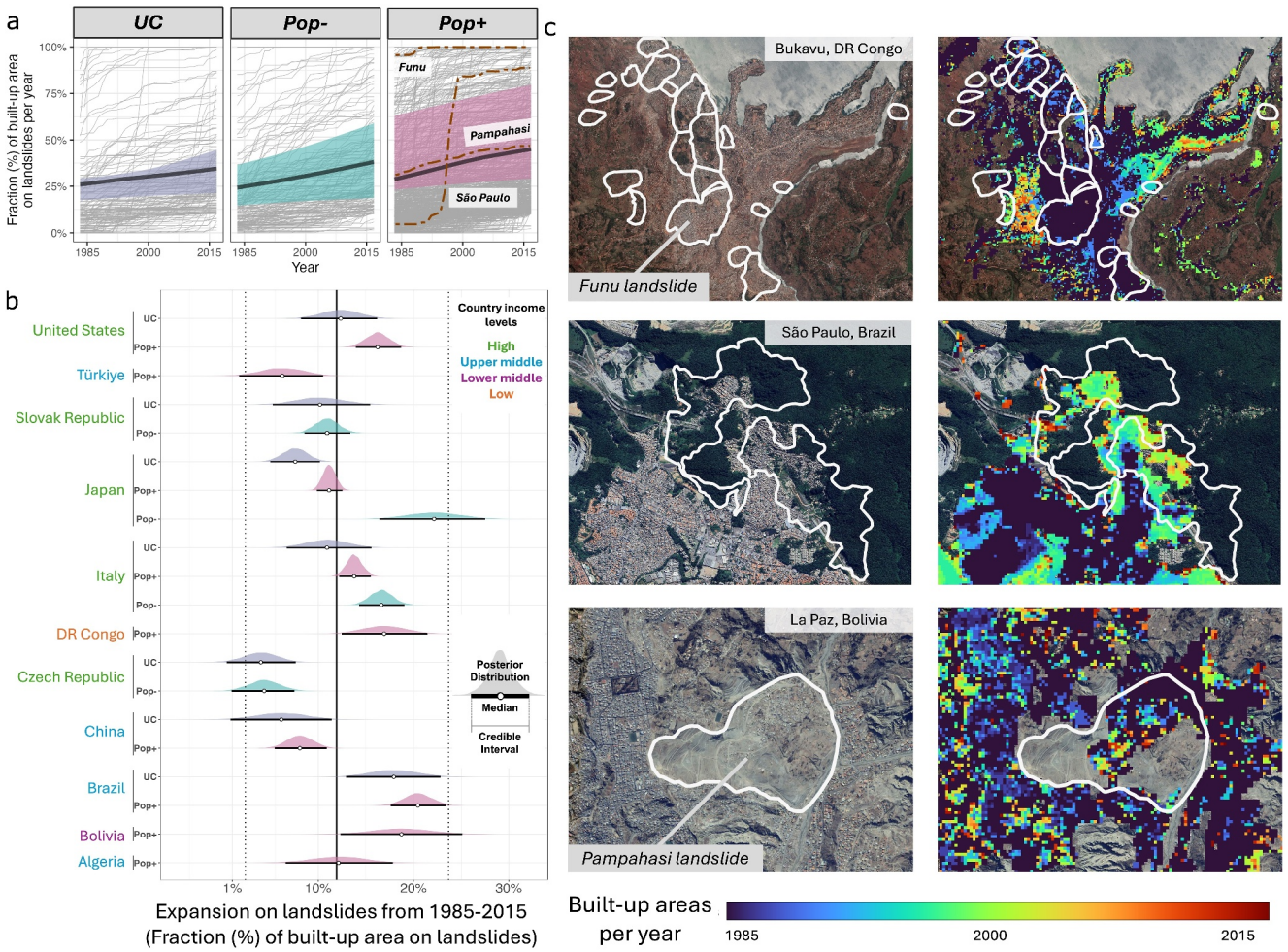

Figure 3. *Growing landslide exposure influenced by mountain population trends*. (a) Changes in the fraction of urban built-up areas on landslide areas from 1985 to 2015 for three groups of differing population trends (urban centers: *UC*, *Pop+*, and *Pop−*). Thick black lines are posterior means and shaded regions are 95% posterior predictive highest density intervals (HDIs). Light gray lines are time series of individual landslides. (b) Country- and population-level 30-year trends of built-up areas on landslides. Distributions are predictive posterior growth rates of built-up area on landslides, color-coded to trends in panel (a). White dots are medians and thick horizontal lines are 95% HDIs; thick black vertical line is pooled median and dotted lines are 95% HDIs. Countries are labeled by income levels classified by per capita income in 2015 (United Nations Department of Economic and Social Affairs, 2014). (c) Built-up areas expanding on landslides from 1985 to 2015. We show satellite images of known landslides (white outlines) embedded in cities in the right column. Spatial data showing urban areas expand on large landslides over 30 years, using WSF-Evo settlement footprints (Marconcini et al., 2021). Source: Google Earth Imagery; Bukavu, 2016; São Paulo, 2015; and La Paz, 2014.

these countries are represented by only a single city in our database. Twelve cities each had more than 10,000 people exposed to landslides in 2015, led by Bukavu, DR Congo (127,000 people) and La Paz, Bolivia (42,000 people). Known landslides affect ∼1% of the metropolitan areas of two megacities that host more than 10 million people; some 11,000 people live on landslides in São Paulo, Brazil, and 10,000 in Los Angeles, United States.

3.2. Influence of Mountain Population Trends

Built-up areas on landslides in cities have generally increased from 1985 to 2015 (Figure 3a). We estimate that the overall averaged built-up areas on landslides expanded by 12^{+12}_{-10}% over 30 years (Figure 3b; Methods: 2). Yet, the posterior means of built-up landslide area remained below 50% for each group. Both sample size and variance are highest in the *Pop+* mountain region, with a wide range of expansion patterns onto landslides (Figure 3c) and the largest proportion of landslides with low built-up areas.

Landslides in Brazil and the United States credibly exceed this pooled median, whereas the fractions of built-up areas are credibly lower in China and the Czech Republic. Estimates for the remaining countries of Slovak Republic, Türkiye, Bolivia, and Algeria are largely indistinguishable from the global estimate. On the contrary,

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the (lower) trends of expanding built-up areas on landslides in urban centers (*UC*) were largely indistinguishable from those in mountain regions of declining populations (*Pop*−) in the Czech Republic and Slovak Republic (Figure 3b).

4. Discussion

4.1. Role of Population Dynamics

Our global sample of large, urban landslides shows that built-up areas across cities have expanded on landslides between 1985 and 2015, irrespective of differences in countries' per capita income levels (Figures 2c and 3a). Our models show that built-up areas grew faster onto landslides in *Pop*+ mountain regions than in the urban centers (*UC*), at least in Brazil, China, and the United States (Figure 3b; Methods: 2). Yet, landslide exposure also rose in *Pop*− mountain regions, although less rapid (Figure 3a). We surmise that landslide exposure may be elevated in areas within commuting distances from urban centers; these peripheral areas of many cities see combined pressure from inbound migrants from rural mountain areas (Bachmann et al., 2019) and the outbound search for affordable housing (Perlik & Membretti, 2018). Of all areas with declining populations studied here, building activity on large landslides was most widespread in Japan and Italy, where exposure could have increased with expanded efforts to stabilize and mitigate large landslide impacts. In Japan, nationwide efforts to mitigate deep-seated landslides under the Sediment Disaster Prevention Act of 2000 (Junichi & Naoki, 2020), while in Italy countermeasures can be deployed in urban areas to stabilize actively moving landslides (Guerriero et al., 2021). Mitigation measures addressing risk from different landslide types have made fatalities in rural regions decrease from 1945 to 2015 alongside trends of migration to urban areas (Shinohara & Kume, 2022). Hence, the commensurately rising population pressure in Japanese urban centers may have increased the exposure to landslides, thus counteracting against growing efforts to manage landslide risk.

Growing cities in mountain areas may need to venture onto terrain that is suboptimal or even unsuitable for permanent buildings and infrastructure. We find in Buvaku, DR Congo, and La Paz, Bolivia, that the average terrain steepness of urban centers is comparable to that of their surrounding mountains (Figure 4a). Yet, the rapid growth of Bukavu led to its expansion onto landslides, within the city, perched on more steeply inclined terrain (Figure 2c). While most of the occupied landslides underlying the city may be dormant (Dewitte et al., 2021; Dille et al., 2022), the slow-moving Funu landslide alone is estimated to host 80,000 inhabitants in a densely populated neighborhood with a recent growth of dense informal settlements (Michellier et al., 2020). While the Funu landslide had been nearly fully inhabited since 1995 (Figure 3a), our data shows that new neighborhoods have established their presence on large landslides (Figure 2c). Similarly, densely built-up neighborhoods on landslides could rise sharply in other African and Asian cities that may host 90% of the projected 2.5 billion urban residents by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2019).

Many cities have established metropolitan corridors that connect rural to urban communities, thus leading to a rise in growth of smaller cities and towns in mountain regions (Cattaneo et al., 2021; Depicker et al., 2021; Thornton et al., 2022). Some of these growing towns that build on steep and deceptively quiescent terrain may find themselves increasingly exposed to slow-moving landslides (Ferrer et al., 2024). For example, a large landslide that underlies most of the Himalayan town of Joshimath, India, suddenly accelerated in 2023, prompting mass evacuation (Sreejith et al., 2024) and severely damaging more than half of all buildings (Chourasia et al., 2024). Hence, the trends of landslide exposure observed in our study may significantly extend to peri-urban areas outside of the metropolitan commuting regions, small cities, and hill towns at the fringes of urban centers, where roughly two-thirds of the mountain population reside (Ehrlich et al., 2021).

4.2. Informal Settlements Occupy Steeper Slopes

Urbanization has been accompanied by increasing poverty and the rise of many informal settlements; often communities are forced to occupy hazardous locations of low economic land values (Maricato, 2017; Santos, 1993) with buildings that lack structural integrity, especially in terrain prone to landslides (Bastos Moroz & Thieken, 2024; Ozturk et al., 2022). In Brazil, for example, parts of urban areas have rapidly covered landslides at rates above the global average (Figure 3b). Thousands of people in São Paulo, Brazil, are exposed to several large landslides (Figure 2), with buildings perched on much steeper slopes (14°) than those in the urban center (7°, Figure 4a). The growth of these built-up areas on landslides in São Paulo has markedly accelerated since 2000 (Figures 2c, 3a, and 3c), likely as a consequence of intensive urban development driven by migration and

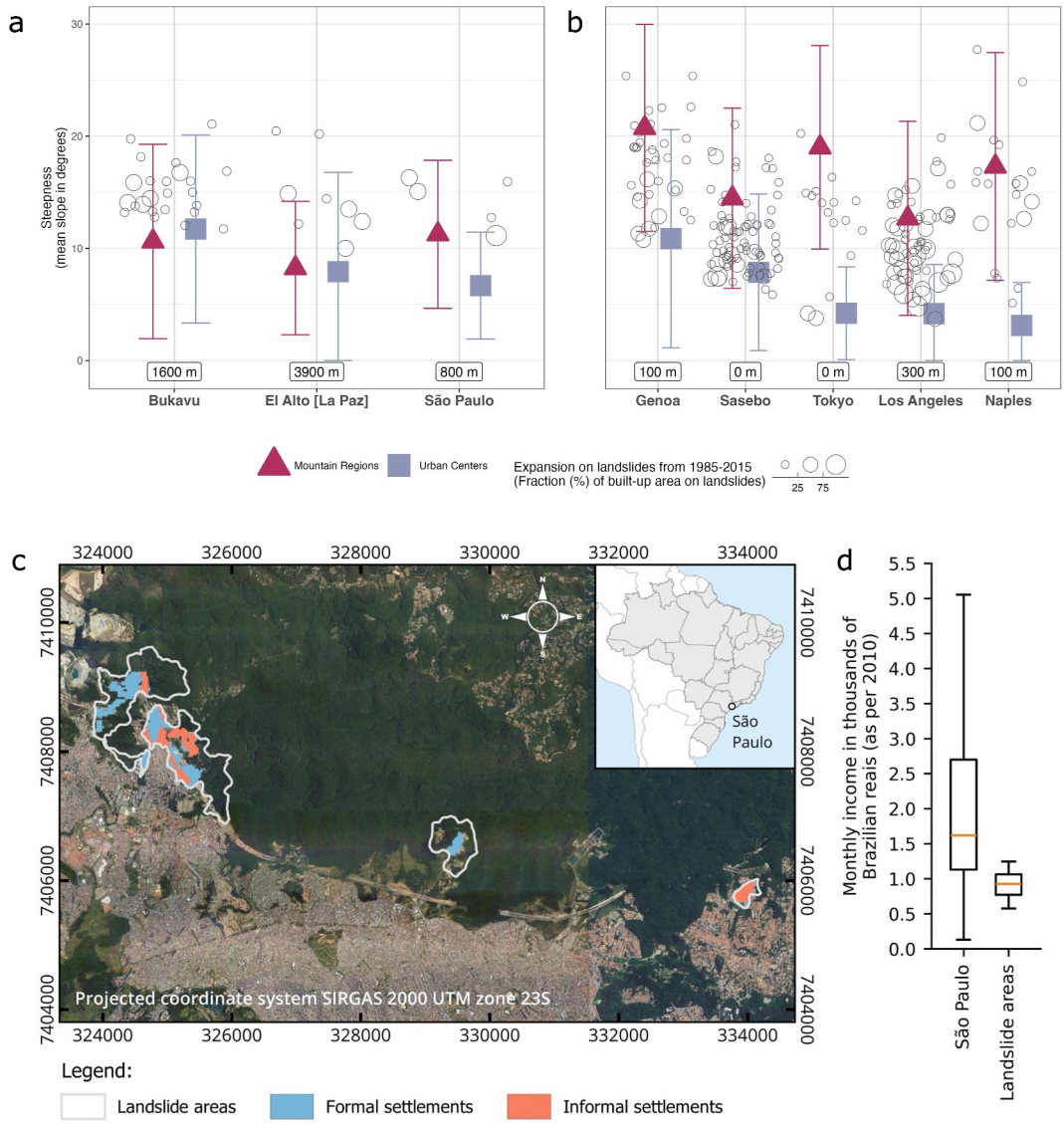

Figure 4. *Landslides on steep slopes host urban settlements*. Mean slope steepness of built-up landslides (jittered bubbles scaled by growth rate), estimated from the Shuttle Radar Topography Mission digital elevation model (Farr & Kobrick, 2000) in panel (a), mountain cities and (b), coastal cities; mean elevations (m a.s.l.) of urban centers on top of *x*-axes. Box and whiskers refer to urban centers and those of their surrounding mountain regions (Snethlage et al., 2022); error bars are standard deviations from the mean. Urban settlements on landslides in São Paulo, Brazil, showing (c), non-informal and informal settlements on landslides (IBGE, 2019); (d), box plots of monthly incomes in Brazilian Reais (BRL) in São Paulo and its landslide areas, according to Brazilian census of 2010 (IBGE, 2010); Source in panel (c): Google Earth Imagery.

population growth in past decades (Santos, 1993). By 2015, informal settlements had made up 6% of all urban areas of São Paulo, while 38% of built-up areas on landslides were informal (Figure 4c). Based on the 2010 census, the median monthly income of people living on landslides was about half that of the city-wide median (Figure 4d).

We surmise that urbanization and poverty could further raise landslide exposure, as vulnerable communities resettle onto hazardous areas despite severe previous landslide impacts. For instance, in La Paz, Bolivia, 60% of the population lived in self-built houses in 2005 (O'Hare & Rivas, 2005), with densely urbanized neighborhoods (*laderas*) clinging to some hillslopes steeper than 50° (Nathan, 2008). These *laderas* are exposed to reactivation along the fringes of dormant large landslides (Roberts et al., 2014), such as the catastrophic collapse of the

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Pampahasi landslide in 2011 (Roberts et al., 2019), or the Kantutani landslide in 2019 (Shan et al., 2023) that cleared entire neighborhoods. The memory of such disasters seems to have faded or been counterbalanced by a higher risk affinity, as we find that built-up areas had reclaimed almost half of Pampahasi landslide by 2015 (Figures 3a and 3c).

4.3. Should Flood-Prone Coastal Cities Retreat Upslope?

Rising sea levels in the wake of climate change will have the potential to incur greater levels of flood hazards may prompt managed retreats (Glavovic et al., 2022; Nicholls et al., 2021; Ohenhen et al., 2024) that could drive parts of coastal cities to higher and drier ground on surrounding hillslopes (Pinter et al., 2019; Tamura et al., 2023). Here we find that built-up areas have expanded on landslides situated on steeper slopes across populous coastal cities in the United States, Japan, and Italy (Figures 2c and 4b). Hence, these expanding cities may experience higher landslide exposure with expansive low-density developments and relocating communities climbing uphill (K. Shi et al., 2023; Taubenböck et al., 2024).

Entire coastal cities may have to relocate in order to adapt to rising sea levels compounded by land subsidence (Tay et al., 2022). Indonesia sets a precedent by relocating its capital, Jakarta in adaptation to imminent submersion by 2050 (Kimmelman & Haner, 2017; Setiadi et al., 2023; Takagi et al., 2016). However, amid the massive effort to establish Nusantara as the emerging capital city, regional hazards assessments reveal that settlers could be exposed to a cascading risk of floods triggering landslides (Heo et al., 2024). Hence, feasibility studies of managed retreats to clear flood-prone areas (Hino et al., 2017) and relocate communities onto higher elevations with steeper slopes may need to consider changes to landslide exposure and risk as possible trade-offs. Managing such risk begins with estimating exposure, and will require expanded monitoring efforts and assessments of known urban landslides; a task that may be achieved with ground deformation tracking through satellite optical or radar remote sensing (van Natijne et al., 2022; Van Wyk de Vries et al., 2024), but essentially supported by extensive field insight and validation (Dille et al., 2022).

4.4. Implications for Expanding Cities

Our results are selective, though compelling, city- and nation-wide snapshots of the how exposure of cities to large (>0.1 km^2) landslides has doubled between 1985 and 2015. Globally, we anticipate a much higher number of people exposed, especially if we consider smaller and more frequent urban landslides. For example, almost 60% of the 28 million residents of Mumbai, India, live in slum areas, out of which 70% are landslide-prone (Rangwala et al., 2024), albeit to much smaller and more frequent failures than the large landslides we considered here. Most cities have less than 1% of their areas, and fewer than 1,000 people, present and living on these landslides (Figure 2b). These seemingly low exposure estimates could indicate that people have recognized and avoided the hazards from such slope instabilities. An alternative explanation is that more complete inventories of large landslides in cities may have simply eluded our study. In many cities, especially in the Global South, detailed and comprehensive multi-temporal landslide inventories remain uncommon (Dewitte et al., 2021; Kubwimana et al., 2021). Moreover, we have no data about cities in the Himalayas and South American Andes, although landslide problems are known in these regions (Nieto et al., 2025; Van Wyk de Vries et al., 2024). Hence, an unknown number of cities potentially exposed to landslides likely remains uncharted. Our estimates of the exposed population thus remain samples that attest to the very minimum level of exposure to known, mapped landslides in urban areas through 2015.

To this end, we offer trends of large landslide exposure in cities amid mountains and along coasts over three decades (Figure 4) and show how these trends are variably influenced by differing demographic trends across countries (Figure 3b). We infer that some cities may have already established suitable policies to manage landslide exposure in the light of urban areas sprawling toward steeper terrain. Thus, we see an opportunity in the upcoming IPCC *Special Report on Climate Change and Cities* (Prieur-Richard et al., 2019) to promote policies that deal better with changes in landslide exposure. Cities play a pivotal role as drivers and bearers of impacts of global environmental change (Bai, 2023; Bai et al., 2018). Hence, more evidence of both the current and projected exposure of urban populations to landslides should be integrated into future development policies across cities.

Critically, immediate attention may go toward an escalating exposure of informal neighborhoods that hosted approximately 1 billion people in 2020, and are projected to grow by 2 billion by 2050 (United Nations Department of Economic and Social Affairs, 2023). Policy addressing socially marginalized communities living

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in informal settlements perched on steep slopes has to intervene in order to prevent growing exposure to landslides. To address this, we recommend integrating participatory landslide mitigation with neighborhood upgrading strategies that are collaboratively designed with landslide-exposed communities. Successful examples of such community-led initiatives can be seen in Colombia (Smith et al., 2020), Brazil (Smith et al., 2022), and Indonesia (MacAfee et al., 2024). Our approach can further be refined with the introduction of high-resolution temporal land use data or data on socio-economic and demographic characteristics that can serve as predictors for permanent structures with people on large landslides. Thus, these enhancements to our models could enable policy makers to quantify the effectivity of such urban disaster risk reduction policies across countries on the component of landslide exposure defined in our study. Here, we limited our selection to mountain areas delineated in the GMBA and population trends from the GHS-POP data. Future work to incorporate populations projections into our models may want to consider that the variability of the estimated global share of mountain population ranges from <5% to >31%; contrasting delineations of mountain areas contribute to this variance on top of different population sources (Thornton et al., 2022). Moreover, modeling the interactions between informal settlements and landslides should be at the forefront of decision-making to identify measures to landslide exposure and mitigate risk (Bozzolan et al., 2023; Ozturk et al., 2022). We emphasize that recognizing and incorporating landslide exposure in key policies supports cities to remain resilient against the impacts of global environmental change, while reducing poverty and inequity.

Data Availability Statement

All codes and model data used for the statistical analysis and figures in the study are openly accessible and available at Zenodo via (Ferrer, 2025) (https://doi.org/10.5281/zenodo.14871068). Outlines for urban center and metropolitan region from Global Human Settlement Layer (Moreno-Monroy et al., 2021; Schiavina et al., 2019) (https://human-settlement.emergency.copernicus.eu/). World settlement footprint evolution (Marconcini et al., 2021) data was accessed through the German Aerospace Agency (DLR) geoservice (https://geoservice.dlr.de/web/maps/eoc:wsfevolution).

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