Nat. Hazards Earth Syst. Sci. Discuss., 3, 2777–2809, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/2777/2015/
doi:10.5194/nhessd-3-2777-2015

Natural Hazards and Earth System Sciences
Discussions
Open Access

Regional trends and controlling factors of fatal landslides in Latin America and the Caribbean

S. A. Sepúlveda[1] **and D. N. Petley**[2,*]

[1]Departamento de Geología, Universidad de Chile, Santiago, Chile
[2]Institute of Hazard, Risk and Resilience, Department of Geography, Durham University, Durham, UK
[*]now at: School of Environmental Sciences, University of East Anglia, Norwich, UK

Received: 30 March 2015 – Accepted: 31 March 2015 – Published: 24 April 2015

Correspondence to: S. A. Sepúlveda (sesepulv@ing.uchile.cl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

A database of landslides that caused loss of life in Latin America and the Caribbean in the period from 2004 and 2013 inclusive has been compiled using established techniques. This database indicates that in the ten year period a total of 11 631 people lost their lives across the region in 611 landslides. The geographical distribution of the landslides is very heterogeneous, with areas of high incidence in parts of the Caribbean (most notably Haiti), Central America, Colombia, and SE. Brazil. The number of landslides varies considerably between years; the El Niño/La Niña cycle emerges as a major factor controlling this variation, although the study period did not capture a large event. Analysis suggests that on a continental scale the mapped factors that best explain the observed distribution are topography, annual precipitation and population density. On a national basis we have compared the occurrence of fatality-inducing landslide occurrence with the production of research articles with a local author, which shows that there is a landslide research deficit in Latin America and the Caribbean. Understanding better the mechanisms, distributions causes and triggers of landslides in Latin America and the Caribbean must be an essential first step towards managing the hazard.

1 Introduction

Landslides are a ubiquitous hazard, occurring in every high relief area of the world, and a significant source of loss of life in such terrains. Regions such as South Asia and South America are characterised by high tectonic uplift rates, which lead to steep, unstable slopes; and populations that are concentrated in deep valleys prone to catastrophic landslides. Thus, the background landslide risk is comparatively high. It is widely considered that landslide vulnerability in mountain environments is further increased in areas of dense urbanization and/or where precarious squatter settlements have developed on, or at the foot of, steep slopes in poor or developing countries (Alexander, 2005). Such is the case of large Latin American cities such as Rio de Janeiro, Caracas or Valparaiso.

The acquisition and analysis of historic data of casualties due to landslide events is key for the evaluation of risk, as found in regional studies (e.g. Evans, 1997; Guzzetti, 2000; Guzzetti et al., 2005; Salvati et al., 2010). On a global basis, Petley (2012a, 2012b) compiled a database of landslides that caused loss of life for the period 2004 to 2010, demonstrating that losses were considerably higher than had previously considered. In those studies, a number of hotspots of landslide activity were identified, most notably in parts of China, S. Asia, SE. Asia, the Caribbean, C. America and S. America. However, detailed analysis of each of these areas was not undertaken.

A disadvantage with the original study was that most of the data acquisition was undertaken using English language textual searches. Petley (2012b) noted that this might cause an under-sampling in those areas with low penetration of English, especially for example Latin America.

This study seeks to provide a better understanding of the distribution of landslides that cause loss of life in the Caribbean and Latin America. In doing so, this study extends the original database by using search terms in local languages (most notably Spanish) and by including a longer time period (ten rather than seven years). Thus, it seeks to provide a better understanding of the spatial and temporal distribution of landslide losses in this area.

2 Methodology

Data on the occurrence of landslides that resulted in loss of life worldwide has been collated since September 2002 in the Durham Fatal Landslide Database (DFLD). The methodology through which the data is collected has been described in detail in Petley et al. (2005, 2010), and analyses of the dataset through to 2010 are presented in Petley (2012a, 2012b). The dataset has also been used for analyses of specific aspects of landslide impacts, such as the relationship with climate in South Asia (Petley et al., 2010) and the occurrence of fatality-inducing landslides associated with large dams (Petley, 2013).

In brief, the dataset is compiled through a combination of a daily internet search with pre-determined keywords, plus the use of the research literature; government and aid agency reports; and in some cases direct correspondence. The dataset includes all mass movements, including landslips, debris flows and rockfalls, but snow and ice avalanches, and hyperconcentrated flows, are excluded. The dataset includes anthropogencially-induced landslides.

The location of each landslide is identified using a range of tools, primarily the National Geospatial Intelligence Agency's Geonames Search Engine (http://geonames.nga.mil/namesgaz), supplemented with the use of Google Earth and similar tools. The location of each landslide is generally identified to within about 2 km; no attempt is made to more precisely locate them as this would be an extremely challenging task, and would generally not be possible from the available information. For about 10 % of landslides it is impossible to identify a useful location.

The reliability of the dataset is described in Petley et al. (2005) and Petley (2012a). In general the dataset probably slightly underestimates the occurrence of fatality-inducing landslides for two key reasons:

1. The dataset inevitably fails to capture some smaller events, especially in remote mountainous areas. However, it is likely that such events represent a small proportion of the total number of fatalities;

2. The dataset probably fails to register all of the deaths associated with some larger landslide events, most notably those victims who succumb to injuries after being recovered from the landslide.

In common with other natural hazard impact datasets, the greatest errors in terms of losses are likely to occur in the largest events, when it can be difficult to determine reliably the total losses. This can be particularly pertinent in the case of very large

NHESSD
3, 2777–2809, 2015

S. A. Sepúlveda and D. N. Petley

landslides in poor countries in which the recovery of bodies is generally not practicable, and the ability to ascertain exactly who has been killed is limited.

In this study, an entirely separate attempt was made to compile a landslide fatality dataset for South and Central America, and the Caribbean. In this case the search used key terms in Spanish. The difference between the two datasets was found to be small; the Spanish-based dataset increasing slightly (by about 5 %) the number of events, the great majority of which were associated with low levels of losses, in comparison with the original dataset. The analysis presented here uses the combined dataset (Table 1), termed here the Enhanced Durham Fatal Landslide Database (EDFLD).

We have examined the improved dataset in the context of a range of physical and social datasets as follows:

- Topographic parameters such as slope gradient were obtained from the Shuttle Radar Topography Mission with 30 m resolution (SRTM30).
- The regional geology was obtained from the Geological Map of the World (CGMW, 2010).
- Rainfall data was acquired from the Global Precipitation Climatology Center (GPCC) 1 and 0.5° datasets (Schneider et al., 2011a, b).
- The regional seismicity was characterized using the data from the Global Seismic Hazard Map Project (GSHAP; Giardini et al., 1999, 2003).
- National population and development data were obtained from the United Nations 2012 World Population Prospects (United Nations, 2013) and the 2013 Human Development Report (UNDP, 2013).
- The country corruption factor, which have been identified with a strong positive correlation with casualties during earthquakes (Ambraseys and Bilham, 2001; Escaleras et al., 2007), was obtained from Transparency International Corruption Perceptions Index (Transparency International, 2013).

NHESSD
3, 2777–2809, 2015

– The spatial population density for the year 2000 mapped by the NASA Earth Observatory based on data from the Socioeconomic Data and Applications Center (SEDAC) of Columbia University (NEO, 2014). Whilst data from 2000 is now somewhat out of date, it is remains one of the best such comprehensive datasets available.

3 Results

3.1 Fatal Landslides in Latin America and the Caribbean 2004–2013

The EDFLD recorded in Latin America and the Caribbean a total of 611 landslides causing 11 631 deaths in the ten-year period between 2004 and 2013 inclusive (Fig. 1 and Table 1). Fatal landslides were recorded in 25 countries (seven in Central America, nine in South America and seven in the Caribbean; Fig. 2 and Table 1). The year with the most fatal landslide events was 2010 (133 cases) while the lowest number was registered in 2004 (21). Other years with high landslide activity were 2005, 2008, 2009 and 2011 (Fig. 1). While the number of cases is mainly dominated by small landslides with a few casualties, the annual number of fatalities is strongly influenced by a low number of catastrophic events (Fig. 1). Surprisingly, the year with the highest recorded number of deaths caused by landslides was 2004 (3865), which is the year with smallest number of fatal events. This is controlled by a landslide disaster in September 2004 triggered by Hurricane Jeanne in Haiti, causing over 3000 casualties. Other years with high fatality records are 2005 (2076 deaths, over half of them from a single large event in Guatemala), 2008 (1199 fatalities, almost half of them from another hurricane-induced event in Haiti), 2010 (1277 fatalities) and 2011 (1688 records), the latter two heavily influenced by multiple rainfall-induced landslides in Brazil.

Nearly 90 % of the recorded cases in the EDFLD were triggered by rainfall (Fig. 3). Most of them (74 %) were induced by intense rainstorms, while 15 % were clearly identified as related with a hurricane or tropical storms (TS), mainly in Central America and

NHESSD
3, 2777–2809, 2015

the Caribbean. Only 4 % of the cases were induced by earthquakes, with the remainder being associated with construction, mining or volcanic activity. In terms of fatalities it is remarkable to note that the hurricane-related cases represents over 50 % of the deaths (Fig. 3), and even this might be undersampled as in such events landslide deaths are often not identified as such. Nevertheless, it is important to note that in the 10 year study period there were no cases of extremely large, catastrophic landslides induced by seismicity (such as the 1970 Huascaran earthquake in Peru; Evans et al., 2009), volcanism (such as the 1985 Nevado del Ruiz eruption in Colombia; Pierson et al., 1990) or rainfall (such as the 1999 Vargas disaster in Venezuela; Bezada, 2009). In each case these earlier events caused over 15 000 deaths. We note that the study period is not associated with a very strong El Niño event, which may be significant in terms of the long term pattern of landslide incidence (see below).

The frequency distribution of the annual data as well as the whole dataset shows a strong inter-annual consistency (Fig. 4), although for events with more than a few hundred of fatalities there are no records for many years. There is a slight reduction in gradient for events with small number of deaths, which has also been identified for the global database (Petley, 2012a). This is probably due to undersampling of small cases, especially from some countries where the number of records is surprisingly low or even null (for example Bolivia and Cuba, respectively). However, there is no "rollover" for the smallest landslide events in the fatality data, as is found for landslide volume and area (Malamud et al., 2004) datasets, except in the case of a small number of the annual curves.

3.2 Temporal and Spatial Distribution and Controlling Factors

The annual total data shows high levels of inter-annual variability in the temporal distribution of events (Fig. 1). However, the annual patterns suggest some seasonality, which is unsurprising given that most of the cases are related to climatic conditions (Fig. 5). In terms of the number of landslide events, peaks occur early in the year and in the September–November period, with the highest peak in early October. The fatal-

NHESSD
3, 2777–2809, 2015

ity record generally coincides with this, but the influence of single catastrophic events generates a much noisier dataset.

This seasonality in the number of fatal landslides has a strong correlation with precipitation patterns at a sub-continental scale, as is the case for Asia (Petley, 2010). The annual precipitation cycle differs between regions, and the landslide record tends to follow these changes (Fig. 6). While in Central America and the Caribbean the hurricane season, mainly between September and November, controls the landslide temporal distribution, in South America it is large storms in November–January and March–April that have a strong influence, especially in rainy countries such as Brazil and Colombia, and to a lesser extent in the arid Andean highlands of southern Peru, Bolivia and northern Chile, where summer-early fall rain periods are the main trigger of landslides and debris flows (e.g. O'Hare and Rivas, 2005; Carreño et al., 2006; Sepúlveda et al., 2014). The clear positive correlation between the number of fatal landslides per month and monthly precipitation can be also compared for each region (Fig. 6d), showing that the number of events is higher in Central America for moderate to low precipitation, while for the largest rainfall amounts tend to produce more cases in South America.

The countries with the highest number of fatal landslides in the studied period are (in decreasing order) Brazil, Colombia, Mexico, Guatemala, Peru and Haiti. The same six countries record the largest amount of fatalities, in this case led by Haiti (Table 1). The seasonal variations discussed above are mainly controlled by landslide activity in these countries.

The spatial distribution of landslides causing death may be controlled by both natural and human factors, and may vary strongly even within a country. We have undertaken a first order, coarse-scale analysis of the relationship between a series of natural and social conditioning factors and the landslides in the EDFLD. For this first-order analysis, we use slope gradient to account for relief and regional lithology to illustrate the natural controlling factors (Fig. 7). As expected, landslides tend to occur in high gradient areas such as the Andean range in South America and hilly zones in Central America and the Caribbean. However, some gaps can be observed, for example in the eastern slope of

NHESSD
3, 2777–2809, 2015

the Altiplano plateau in Bolivia and northern Argentina, and in northern Mexico, illustrating that these topographic factors cannot solely explain the landslide distribution. The regional lithology factor (Fig. 7) is even less clear, although it can be observed that most landslides occur in regions dominated by igneous and metamorphic rocks, which tend to coincide with higher slopes. However, as the local geology is likely to be a key fact determining the occurrence of landslides, it is not possible to analyze much further at this scale.

As commented before, most of the landslides of the database were triggered by heavy rainfall, and to a lesser extent by earthquakes. Figure 8 shows the fatal landslide distribution in comparison with regional seismicity, represented by the GSHAP seismic hazard map by Giardini et al. (1999, 2003) and mean precipitation in the studied period (GPCC, Schneider et al., 2011a). Given the tectonic setting, the Andean range in western South America as well as Central America and the Caribbean islands are seismically very active, showing a good coincidence with landslide locations. However, given that $< 5\%$ of the landslides were induced by earthquakes, this pattern probably relates to the role of tectonics in mountain building and the generation of strong relief that is prone to landslides. However, tectonics are not dominant – Brazil for example is a seismically-passive area with many landslides in the study period, especially along the hills close to the Atlantic shoreline (Fig. 8). This shows that the role of precipitation is key, showing strong correlations with areas of higher landslide activity within countries such as Colombia, Mexico and Brazil. The apparent lack of fatal landslide records in the Andean range of Bolivia, northern Chile and Argentina is likely to be associated with the low rainfall totals in these areas.

As the dataset is focused on fatalities, social factors must also influence the spatial distribution of fatal landslides. Areas where natural conditioning and triggering factors are favourable for landsliding, but which have only small populations, would not be likely to generate many fatal events. At the country level there is a strong correlation between numbers of fatal landslides and the national population, and an even stronger correlation with population density (Fig. 9). The more densely populated areas in hilly

NHESSD
3, 2777–2809, 2015

terrain, such as in central Colombia, SE. Brazil and some Caribbean islands, generate more fatal events, illustrating that higher exposure and vulnerability increase the chances of fatal landslide occurrence. At a national scale, population density (Table 2) has a strong positive correlation with landslide density (Fig. 9).

As discussed by Alexander (2005), the location of dense populations in precarious, informal or poor urban settlements in less developed countries is a critical factor in determining high numbers of fatalities in landslide events. An analysis of settlement type, based on the EDFLD data, indicates that while only 41 % of the fatal landslide events were recognized in poor or informal settlements, 81 % of the fatalities occurred in such locations. We have also examined the relationship with other socio-economic factors such as Gross National Income and the Human Development Index (UNDP, 2013). A weak increasing trend of fatalities induced by landslides can be observed for less developed countries, but the scatter is much higher than for population density. A similar result is obtained when the number of fatalities is compared with an indication of the level of corruption in each country using the Country Corruption Perceptions Index (Transparency International, 2013). Once again this shows a positive trend (i.e. that more corrupt countries tend to have more recorded landslides) but once again the level of scatter is high.

The above analyses indicate that the best representation of the spatial distribution of observed landslides at a regional scale is derived from slope gradient, precipitation and population density maps, as noted by Parker (2010) for the original DFLD. Combinations of these factors improve the relationships further. For example, the direct product of slope and mean annual precipitation generates a good fit to the data, which is improved further when population density is included (Fig. 10). Thus, these three factors should be considered as primary controlling factors of fatality-inducing landslides in the study region.

NHESSD
3, 2777–2809, 2015

3.3 The impact of scientific research on landslides in Latin America and the Caribbean

It is generally accepted that research can play a key role in reducing the impact of natural hazards, especially if the knowledge is properly transferred to national and regional agencies in charge of civil protection, urban planning and emergency response. Petley (2012b) showed that for landslides at a global scale, the volume of research (as indicated by the number of published peer-reviewed articles) has increased substantially in the last two decades, but that this development is geographically heterogeneous. He showed that those countries with the highest levels of research (i.e. with the highest number of landslide articles) generally have lower number of fatalities. Note that the relationship is complex, with levels of research also indicating levels of wider societal investment (in for example infrastructure, emergency response and hazard management), which may also reduce landslide losses. In terms of research however, whilst knowledge obtained from one location may be transferable to another, there are many impediments to transfer such knowledge to less developed countries, including the small number of local researchers, a lack of funding and language differences (Petley, 2012b).

In this study we have undertaken a similar but more detailed analysis for Latin America and the Caribbean. Research papers with "landslide" or "landslides" in the title, abstract or keywords published in the 2004–2013 period were searched in all databases available in the Thomson Reuters ISI Web of Science database (including the Web of Science Core Collection, Scielo and others) for every country with records of fatal landslides in the same period (Table 2). The records were searched by country, using the institutional address of at least one of the authors as a national indicator. A total of 354 academic papers were recorded in the period, from which 62 % are from South America, 30 % from Central America and 8 % from Caribbean countries. In common with the global dataset, there is a notable increase (more than double) in the last decade in the number of academic papers published on landslides in the study area. This increase is strongly driven by the South American countries, and may well have helped to keep the fatalities trend relatively stable despite the increase in population.

The country with most academic papers with at least one local author in the study time period is Mexico with 76 publications, followed by Brazil (69), Argentina (41), Chile (36) and Colombia (29). Figure 12 illustrates the relationship between the number of scientific publications on landslides and the number of fatalities, considering those countries with more than 10 fatalities in the ten-year period. While it is evident that some countries, such as Haiti and Guatemala, have large numbers of fatalities with very little research, for big countries such as Brazil and Mexico the number of casualties is still high even though they are the leaders in scientific publications (Fig. 12). However, the huge differences in national population in the region (Table 2) should be accounted for a more refined analysis. If the number of academic papers and fatalities are both normalized by total national population, clearer patterns can be identified (Fig. 12), with higher rate of fatalities caused by landslides in countries with lower normalized scientific production. The most productive countries in terms of research papers per capita, with over one paper per million people in ten years, are Costa Rica (3.2), Trinidad and Tobago (2.3), Chile (2.1), Jamaica (1.8) and Ecuador (1.1). It is interesting to note that of those only Chile and Ecuador have more than 10 million inhabitants, with other medium and big size countries presenting lower rates of scientific production per capita. Nonetheless, those levels of research are still far from landslide-prone, developed countries, where the same indicator reaches values as high as 40.9 (Norway) or 21.5 (Italy). With better science policies and improved funding schemes, Latin American and Caribbean countries may start to approach countries such as United States (4.3) or Japan (4.6).

4 Discussion

At the coarse scale the spatial incidence of fatality-inducing landslides in Latin America and the Caribbean is primarily the result of a combination of high relief, dense popula-

NHESSD
3, 2777–2809, 2015

tions and large trigger events (over the time period in question, primarily precipitation). Thus, populated, humid upland regions of Brazil, Colombia, Haiti or Guatemala represent zones of high landslide occurrence resulting in loss of life. The role of precipitation is emphasized at the subcontinent scale, where a seasonal pattern is clear in the annual data that reflects the local precipitation cycle (which varies across the region). The mortality rate is higher in less developed countries that undertake little scientific research.

4.1 Precipitation variation and the role of the El Niño Southern Oscillation

For much of Latin America, rainfall events are positively affected by strong El Niño events, especially in southern Andean countries (e.g. Moreiras, 2005; Sepúlveda et al., 2006), while for Colombia an increase of landslide activity has been observed during La Niña periods (Klimes and Ríos-Escobar, 2010). The 1996–1997 El Niño event, the strongest on record to date, was associated with heavy rainfall and large numbers of landslides in the study region. The period of this study coincides with a phase of the El Niño Southern Oscillation (ENSO) in the Pacific (Trenberth, 1997) that has favoured comparatively weak El Niño and strong La Niña events, such that during the study period, no large El Niño events occurred. However, early 2010, which was characterized by moderate El Niño conditions also represents the peak occurrence of fatal landslides in our study, while a weak correlation between La Niña conditions and higher landslide activity can be observed in Colombia and Venezuela, in particular for late 2010–2011.

Thus, the spatial and temporal patterns presented here represent those associated primarily with moderate to strong La Niña periods. It is likely that the spatial and temporal patterns of fatality-inducing landslides will be different during a strong El Niño event. This EDFLD will not properly represent the long-term occurrence of fatality-inducing landslides until such an event is captured. In fact, a study of a smaller dataset between 1993 and 2002 reported by Alexander (2005) returned Venezuela, Nicaragua, Colombia, Haiti and El Salvador as the Latin American or Caribbean countries with more deaths caused by landslides, showing that there is only partial coincidence with our dataset from one decade later.

4.2 The role of extreme event triggers

The occurrence of a rare but extreme landslide event, such as the 1970 Huascaran rock avalanche (Evans et al., 2009) or the 1999 Vargas debris flows (Bezada, 2009), may multiply the number of casualties by an order of magnitude or more, making it difficult to extrapolate our results to the long term. As shown by Guzzetti et al. (2000), the average number of fatalities per year is extremely variable, but higher in active regions such as the Andes, which is consistent with our results.

A perhaps surprising finding is that during the study period earthquakes triggered only small numbers of fatality-inducing landslides. Latin America and the Caribbean are known to be prone to seismically-induced landslides (e.g. Bommer and Rodriguez, 2002; Schuster et al., 2002) because of the combination of high rates of tectonic activity and steep slopes. The study period captured the largest earthquake in the region in about 40 years (the 2010 Mw = 8.8 earthquake in Chile) and one of the most disastrous earthquakes in term of fatalities and damage in recent times (the 2010 Mw = 7.0 earthquake in Haiti). We think that there is a high probability that the latter is undersampled in terms of landslide-related casualties. This is often the case for earthquakes with large number of fatalities as there is no way to record the phenomenon that caused the loss of life (Petley et al., 2006). There is some photographic evidence that at least some collapses of houses on steep slopes may have been induced by slope failure, but the numbers are unconstrained.

The lack of recorded fatalities from seismically-induced landslides should not be taken to infer that this issue is no longer a problem in Latin America and the Caribbean. Instead, it is the consequence of a paucity of large, shallow earthquakes affecting vulnerable populated areas with steep slopes during the study period. It is likely that the next large earthquake of this type in Latin America and the Caribbean will induce large numbers of fatality-inducing landslides.

NHESSD

3, 2777–2809, 2015

4.3 The World Bank disaster "hotspots" analysis

In a previous assessment as part of the World Bank "hotspots" analysis of natural disasters, Nadim et al. (2006) produced a global-scale landslide hazard and mortality risk map. The EDFLD dataset can be considered to be the realisation of landslide mortality risk over the study period. Whilst in some areas, for example in the Andes and in Central America, there is a good relationship between the landslide and mortality risk maps, in other areas (such as Brazil) the World Bank analysis strongly under-estimates mortality risk. The probable reason for this is that in this approach hazard is assessed by multiplying a number of factors, such as precipitation and seismic hazard. Thus an area of low seismic hazard such as Brazil it tends to generate a comparatively low hazard (and thus risk) score, which therefore fails to capture adequately the true risk in these areas.

However, we also note that the lack of large landslide-inducing seismic events also means that there is no mechanism to benchmark properly the risk from earthquake-induced landslides in Latin America and the Caribbean. This will need further attention in due course.

5 Conclusions

This study has evaluated the occurrence of fatality-inducing landslides in Latin America and the Caribbean in the period 2004 to 2013 inclusive. Over this time period we recorded 611 landslides that caused 11 631 deaths, mostly as a result of rainfall triggers. The geographic distribution of the landslides is heterogeneous, but mostly reflects the combination of relief, precipitation and population density. In urban areas, the presence of informal settlements has a big impact on the number of fatalities, showing the effect of poverty and marginalization.

For the different parts of the study region the occurrence of landslides reflects the annual precipitation. In the longer term the dataset has not captured a strong El Niño event or a series of large earthquakes in landslide prone areas. It is likely that the long term spatial and temporal patterns would be changed when such events are captured properly.

The study also shows that there is a research deficit in terms of landslides in the study area. Increasing understanding of landslides in these regions is likely to be a prerequisite if a meaningful reduction in landslide losses is to be achieved.

Acknowledgements. The authors acknowledge the support of the Durham International Fellowships for Research and Enterprise (DIFeREns, COFUNDed by Durham University and the European Union), for funding a research stay of Dr. Sepulveda at the Institute of Hazard, Risk and Resilience of Durham University. Marisol Lara, Paulina Arellano and Constanza Celis aided with the completion of the database from Spanish-spoken sources and events classification. This research was enabled by the NERC/ESRC Increasing Resilience to Natural Hazards programme under the Earthquakes Without Frontiers project, grant reference NE/J01995X/1, NERC/Newton Fund grant NE/N000315 and Fondecyt 1140317 project.

References

Alexander, D.: Vulnerability to landslides. in: Landslide Hazard and Risk, edited by: Glade, T., Anderson, M., and Crozier, M. J., John Wiley and Sons, Chichester, UK, 175–198, 2005.

Ambraseys, N. and Bilham, R.: Corruption kills, Nature, 469, 153–155, 2011.

Bezada, M.: Natural hazards and human-induced disasters triggered by intense and episodic tropical rains in the Venezuelan mountains, Develop. Earth Surf. Proc., 13, 115–129, 2009.

Bommer, J. J. and Rodríguez, C. E.: Earthquake-induced landslides in Central America, Eng. Geol., 63, 189–220, 2002.

Carreño, R. and Kalafatovich, S.: The Alcamayo and Cedrobamba catastrophic debris flow (January, March and April 2004) in Machu Picchu area – Peru, Landslides, 3, 79–83, 2006.

CGMW: Geological Map of the World, 1 : 25 000 000 scale, 3rd Edition, DVD Edition, Commission for the Geological Map of the World, version 3.0, UNESCO, Paris, France, 2010.

Escaleras, M., Anbarci, N. and Register, C. A.: Public sector corruption and major earthquakes: a potentially deadly interaction, Public Choice, 132, 209–230, 2007.

NHESSD

3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

Evans, S. G.: Fatal landslides and landslide risk in Canada, in: Landslide Risk Assessment, edited by: Cruden, D. and Fell, R., Balkema, Rotterdam, 185–196, 1997.
Evans, S. G., Bishop, N. F., Fidel Smoll, L., Valderrama Murillo, P., Delaney, K. B., and Oliver-Smith, A.: A re-examination of the mechanism and human impact of catastrophic mass flows originating on Nevado Huascarán, Cordillera Blanca, Peru in, 1962 and 1970, Eng. Geol., 108, 96–118, 2009.
Giardini, D., Grünthal, G., Shedlock, K. M., and Zhang, P.: The GSHAP Global Seismic Hazard Map, Ann. Geofis., 42, 1225–1228, 1999.
Giardini, D., Grünthal, G., Shedlock, K. M., and Zhang, P.: The GSHAP Global Seismic Hazard Map. in: International Handbook of Earthquake and Engineering Seismology, International Geophysics Series, 81 B, edited by: Lee, W., Kanamori, H., Jennings, P., and Kisslinger, C., Academic Press, Amsterdam, 1233–1239, 2003.
Guzzetti, F.: Landslide fatalities and the evaluation of landslide risk in Italy, Eng. Geol., 58, 89–107, 2000.
Guzzetti, F., Stark, C. P., and Salvati, P.: Evaluation of flooed and landslide risk to the population of Italy, Environ. Manage., 36, 15–36, 2005.
Klimeš, J. and Rios Escobar, V.: A landslide susceptibility assessment in urban areas based on existing data: an example from the Iguaná Valley, Medellín City, Colombia, Nat. Hazards Earth Syst. Sci., 10, 2067–2079, doi:10.5194/nhess-10-2067-2010, 2010.
Malamud, B. D., Turcotte, D. L., Guzzetti, F., and Reichenbach, P.: Landslide inventories and their statistical properties, Earth Surf. Proc. Land., 29, 687–711, 2004.
Moreiras, S. M.: Climatic effect of ENSO associated with landslide occurrence in the Central Andes, Mendoza Province, Argentina, Landslides, 2, 53–59, 2005.
Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C., and Jaedicke, C.: Global landslide and avalanche hotspots, Landslides, 3, 159–173, 2006.
NEO: Population density gridded map, NASA Earth Observatory, available at: http://neo.sci.gsfc.nasa.gov/view.php?datasetId=SEDAC_POP(last access: 21 March 2014), 2000.
O'Hare, G. and Rivas, S.: The landslide hazard and human vulnerability in La Paz City, Bolivia, Geogr. J., 171, 239–258, 2005.
Parker, R. N.: Controls on the distribution of landslides triggered by the 2008 Wenchuan earthquake, Sichuan Province, China, Unpublished M.S. thesis, University of Durham, Durham, UK, 2010

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

Petley, D. N.: On the impact of climate change and population growth on the occurrence of fatal landslides in South, East and SE Asia, Q. J. Eng. Geol. Hydrogeol., 43, 487–496, 2010.
Petley, D. N.: Global patterns of loss of life from landslides, Geology, 40, 927–930, 2012a.
Petley, D. N.: Landslides and engineered slopes: protecting society through improved understanding, in: Landslides and Engineered Slopes: Protecting Society through Improved Understanding, edited by: Erberhardt, E., Froese, C., Turner, A. K., Leroueil, S., Taylor and Francis Group, London, 3–13, 2012b.
Petley, D. N.: Global losses from landslides associated with dams and reservoirs, in: International Conference on Vajont 1963–2013: Thoughts and Analyses after 50 Years since the Catastrophic Landslide, edited by: Genevois, R. and Prestininzi, Ital. J. Eng. Geol. Environ., Book Series 6, 63–71, 2013.
Petley, D. N., Dunning, S. A., and Rosser, N. J.: The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities, in: Landslide Risk Management, edited by: Hungr, O., Fell, R., Couture, R., Eberhardt, E., Amsterdam, A. A. Balkema, 367–374, 2005.
Petley, D. N., Dunning, S. A., Rosser, N. J., and Kausar, A. B.: Incipient earthquakes in the Jhelum Valley, Pakistan following the 8th October 2005 earthquake, in: Disaster Mitigation of Debris Flows, Slope Failures and Landslides, Frontiers of Science Series, 47, edited by: Marui, H., Universal Academy Press, Tokyo, Japan, 47–56, ISBN:4-946443-98-3, 2006.
Pierson, T. C., Janda, R. J., Thouret, J. C., and Borrero, C. A.: Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars, J. Volcanol. Geoth. Res., 41, 17–66, 1990.
Salvati, P., Bianchi, C., Rossi, M., and Guzzetti, F.: Societal landslide and flood risk in Italy, Nat. Hazard. Earth Sys., 10, 465–483, 2010.
Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC full data reanalysis version 6.0 at 0.5°: monthly land-surface precipitation from Rain-Gauges built on GTS-based and historic data, Global Precipitation Climatology Center, Deutscher Wetterdienst, Offenbach, Germany, doi:10.5676/DWD_GPCC/FD_M_V6_050, 2011a.
Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC full data reanalysis version 6.0 at 1.0°: monthly land-surface precipitation from Rain-Gauges built on GTS-based and historic data, Global Precipitation Climatology Center, Deutscher Wetterdienst, Offenbach, Germany, doi:10.5676/DWD_GPCC/FD_M_V6_100, 2011b.

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

Schuster, R. L., Salcedo, D. A., and Valenzuela, L.: Overview of catastrophic landslides of South America in the twentieth century, in: Catastrophic Landslides: Effects, Occurrence and Mechanisms, edited by: Evans, S. G. and DeGraff, J. V., Geological Society of America Reviews in Engineerin Geology XV, Boulder, Colorado, USA, 1–34, 2002.

Sepúlveda, S. A., Rebolledo, S., and Vargas, G.: Recent catastrophic debris flows in Chile: geological hazard, climatic relationships and human response, Quatern. Int., 158, 83–95, 2006.

Sepúlveda, S. A., Rebolledo, S., McPhee, J., Lara, M., Cartes, M., Rubio, E., Silva, D., Correia, N., and Vásquez, J. P.: Catastrophic, rainfall-induced debris flows in Andean villages of Tarapacá, Atacama Desert, northern Chile, Landslides, 11, 481–491, 2014.

Transparency International: Corruption Perceptions Index 2013, available at: http://cpi.transparency.org/cpi2013/results/(last access: 24 September 2014), 2013.

Trenberth, K. E.: The definition of El Niño, B. Am. Meteorol. Soc., 78, 72271–2777, 1997.

UNDP: Human Development Report 2013, The raise of the South: human progress in a diverse world, United Nations Development Programme, New York, 2013.

United Nations: World Population Prospects: The 2012 Revision, United Nations Department of Economic and Social Affairs, Population Division, New York, 2013.

NHESSD

3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

Table 1. Number of fatal landslides and fatalities for each country with positive cases.

Country	Fatal Landslides 2004–2013	Fatalities 2004–2013
CARIBBEAN		
Dominica	1	3
Dominican Republic	11	48
Grenada	1	1
Haiti	33	4529
Jamaica	10	20
Puerto Rico	2	2
St Lucia	1	5
St. Vincent and the Grenadines	4	9
Trinidad and Tobago	9	12
CENTRAL AMERICA		
Costa Rica	17	97
El Salvador	21	220
Guatemala	64	2264
Honduras	15	70
Mexico	72	493
Nicaragua	3	53
Panama	8	26
SOUTH AMERICA		
Argentina	6	20
Bolivia	6	35
Brazil	119	2262
Chile	15	49
Colombia	110	880
Ecuador	18	101
Peru	38	357
Suriname	1	7
Venezuela	26	68
TOTAL	611	11 631

NHESSD
3, 2777–2809, 2015

Table 2. Population data (United Nations, 2013) and scientific research on landslides indices (ISI Web of Science) for those countries with fatal landslides during 2004–2010.

Country	Population 2010 (thousands)[a]	Pop. Density (persons/km^2)[a]	Research Papers (2004–2013)[b]
CARIBBEAN			
Dominica	71.2	94.8	2
Dominican Republic	10 016.8	206.5	1
Grenada	104.7	304.3	0
Haiti	9896.4	356.6	2
Jamaica	2741.5	249.4	5
Puerto Rico	3709.7	418.0	14
St Lucia	177.4	329.1	0
St. Vincent and the Grenadines	109.3	281.7	0
Trinidad and Tobago	1328.1	258.9	3
CENTRAL AMERICA			
Costa Rica	4669.7	91.4	15
El Salvador	6218.2	295.5	5
Guatemala	14 341.6	131.7	3
Honduras	7621.2	68.0	1
Mexico	117 886.4	60.2	76
Nicaragua	5822.2	44.8	6
Panama	3678.1	48.7	2
SOUTH AMERICA			
Argentina	40 374.2	14.5	41
Bolivia	10 156.6	9.2	3
Brazil	195 210.2	22.9	69
Chile	17 150.8	22.7	36
Colombia	46 444.8	40.8	29
Ecuador	15 001.1	52.9	16
Peru	29 262.8	22.8	15
Suriname	525.0	3.2	0
Venezuela	29 043.3	31.8	10
TOTAL	571 561.1	3460.5	354

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

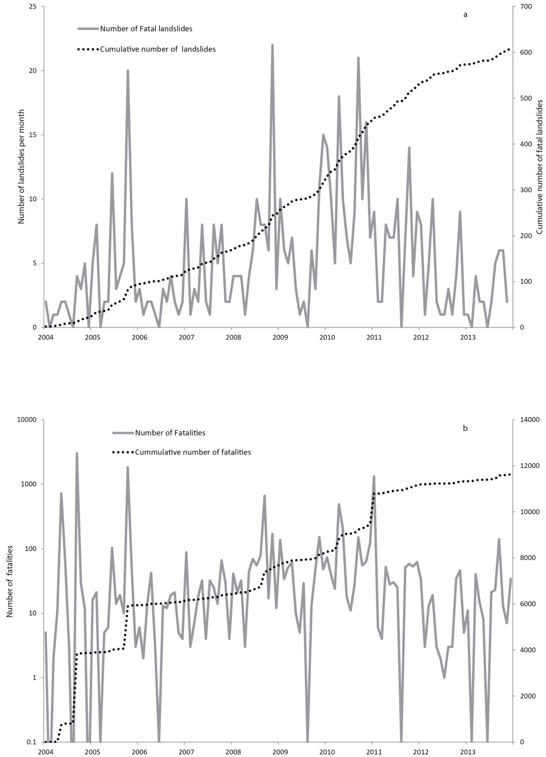

Figure 1. Number of **(a)** fatal landslides and **(b)** fatalities caused by landslides in the period 2004–2013 in Latin America and the Caribbean, based on monthly records. The dotted lines show the cumulative records, showing a smooth curve for the landslides and a stepped curve for the fatalities due to catastrophic events with large number of deaths on single landslides or multiple events in matter of a few days.

NHESSD
3, 2777–2809, 2015

S. A. Sepúlveda and D. N. Petley

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

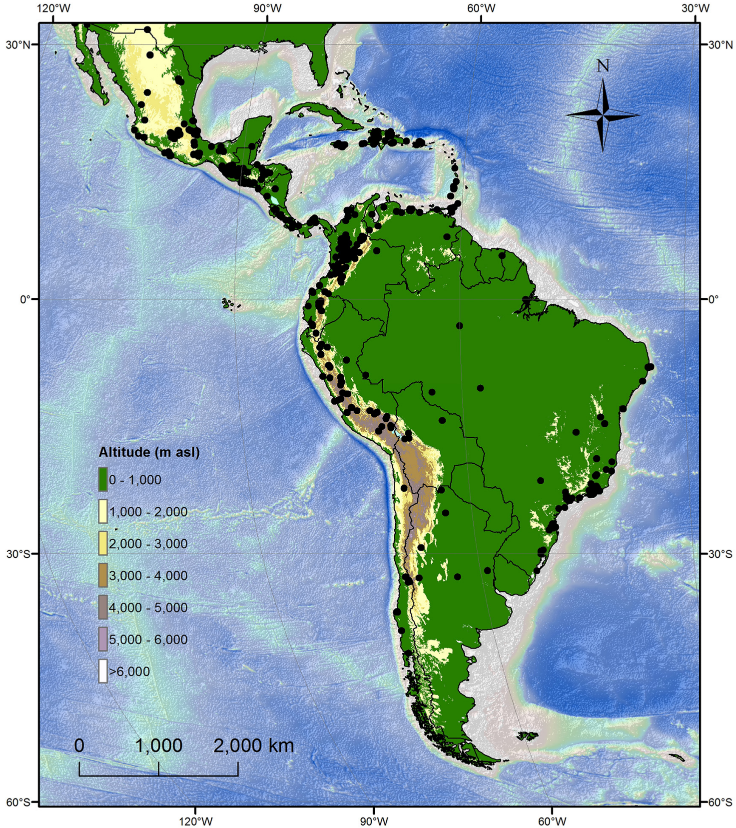

Figure 2. Location of fatal landslides in Latin America and the Caribbean (black dots) in the period 2004–2013 according to the EDFLD.

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

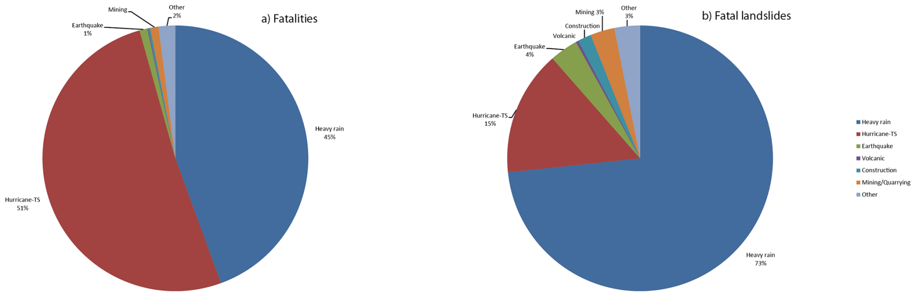

Figure 3. Main triggers of fatal landslides in the studied period. **(a)** Distribution of fatalities and **(b)** distribution of fatal landslides according with the reported trigger for each event.

NHESSD
3, 2777–2809, 2015
Regional trends and controlling factors of fatal landslides
S. A. Sepúlveda and D. N. Petley

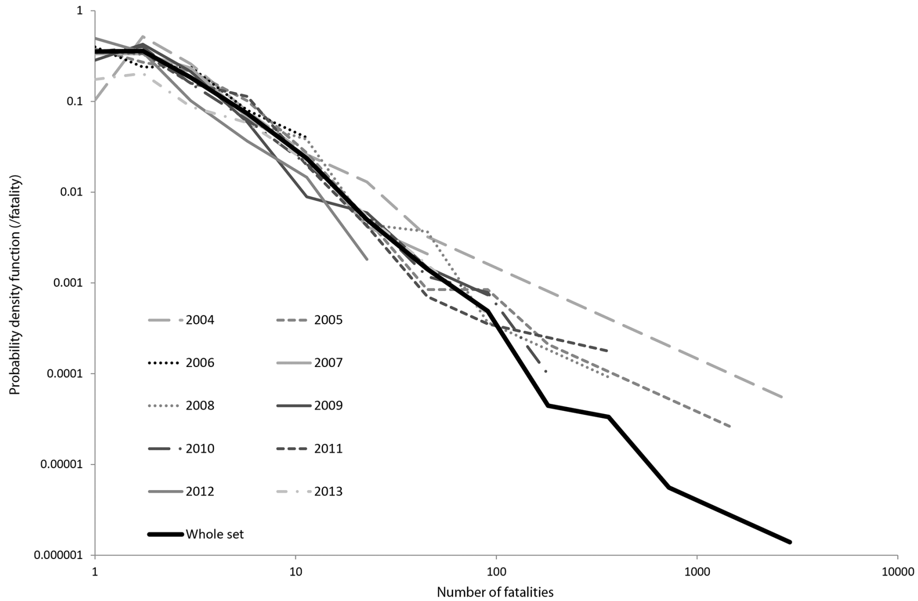

Figure 4. Annual and total probability density functions of fatal landslides for Latin America and the Caribbean.

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

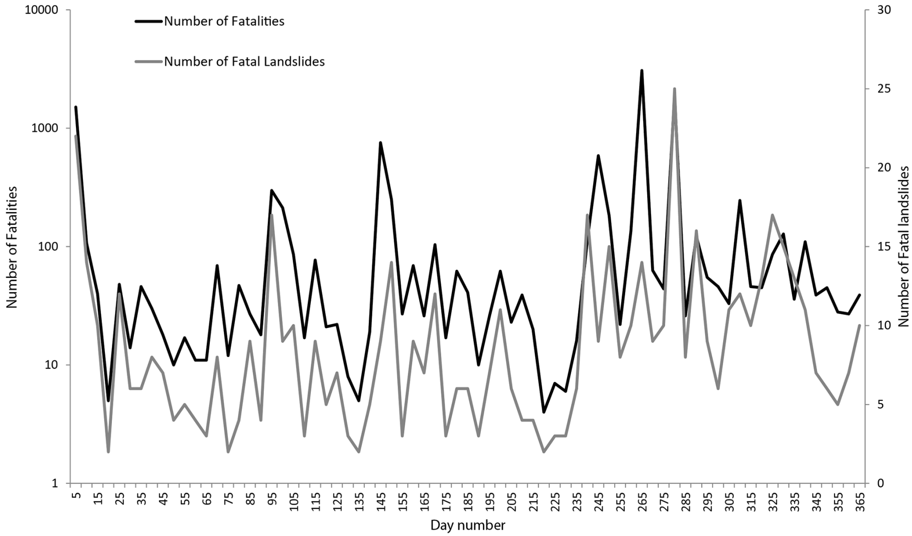

Figure 5. Annual cycle of fatal landslides and fatalities shown in five-day bins (pentads).

NHESSD

3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

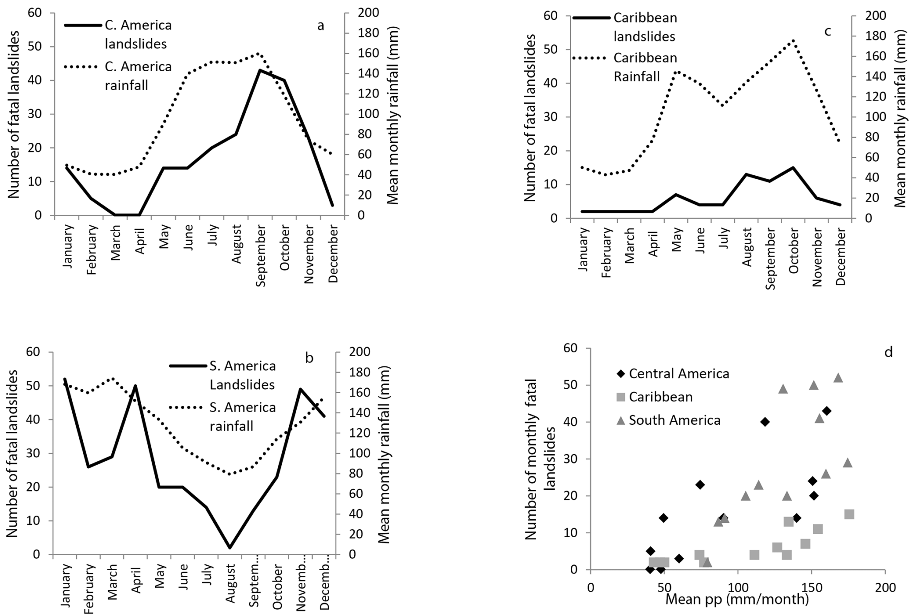

Figure 6. Monthly distribution of landslides in 2004–2013 and mean monthly precipitation in the same period (GPCC 1° dataset, Schneider et al., 2011b) in **(a)** Central America, **(b)** South America and **(c)** the Caribbean; and **(d)** relationship between fatal landslides and amount of monthly rainfall for the three regions.

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

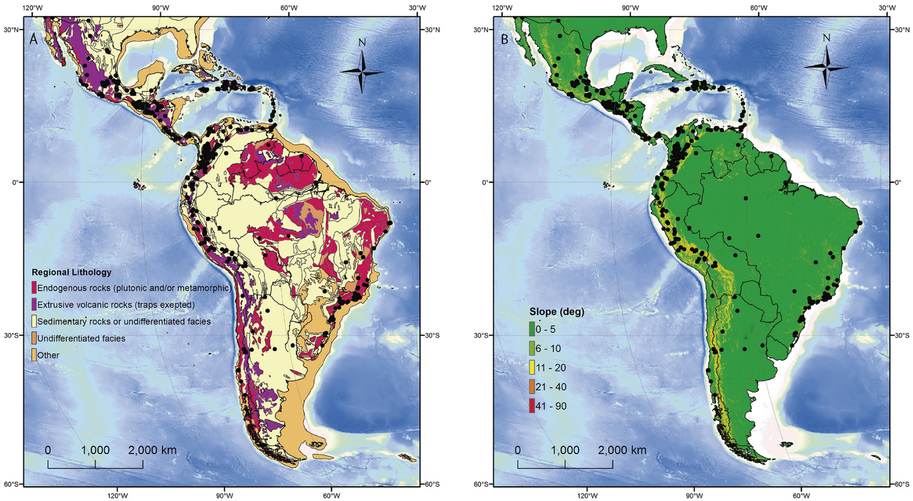

Figure 7. Spatial distribution of landslides (black dots) on top of a geological map (Geological Map of the World, CGMW, 2010, left) and a slope map (STRM30 database, right).

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

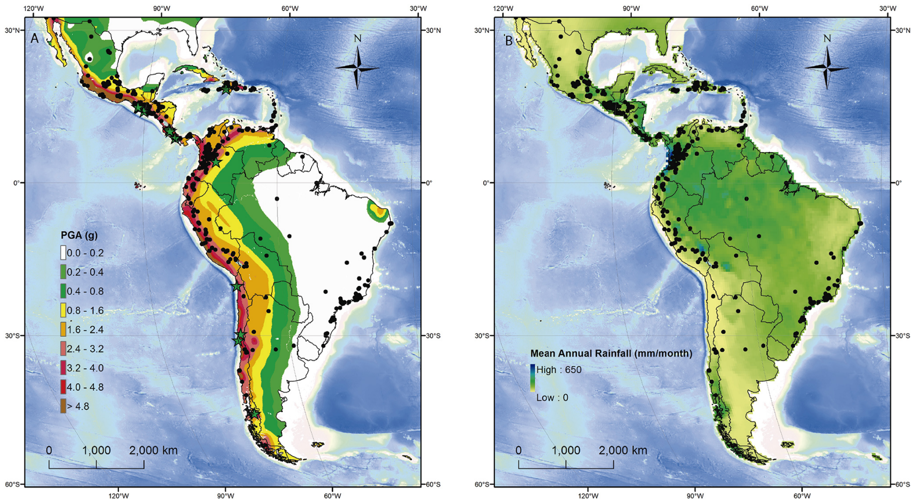

Figure 8. Left: GSHAP seismic hazard map (Giardini et al., 1999, 2003) compared with fatal landslide distribution (black dots). Green stars represent those fatal earthquake-induced landslides in the 2004–2013 period. Right: mean annual precipitation (GPCC 0.5° dataset, Schneider et al., 2011a) map and fatal landslides (black dots) for the 2004–2013 period.

NHESSD
3, 2777–2809, 2015

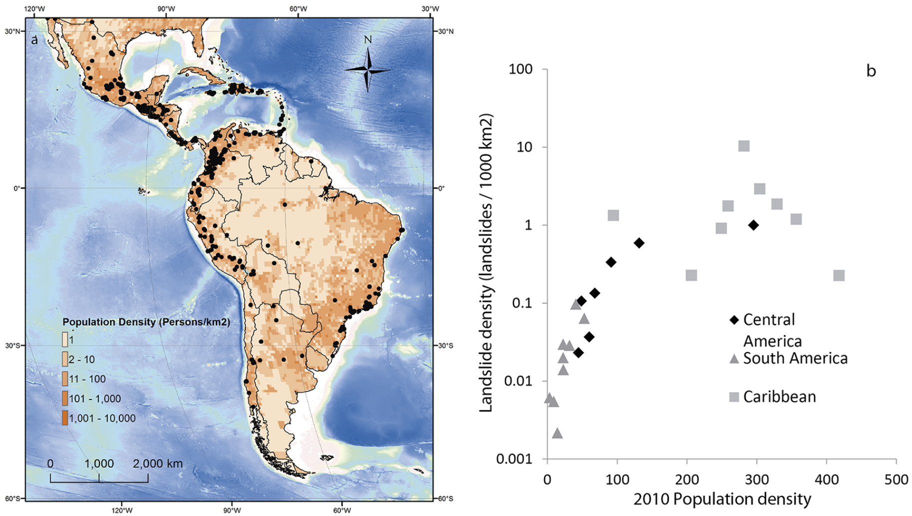

Figure 9. Population density map (year 2000 data, NEO 2014) and fatal landslide distribution (black dots). **(b)** Landslide density vs. population density per country.

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley

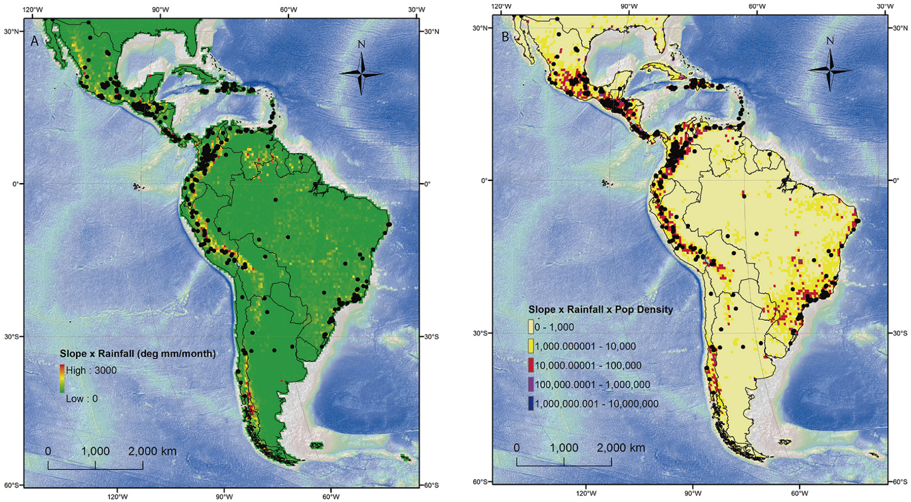

Figure 10. Combined maps of: product of slope and mean annual rainfall (left) and product of slope, mean annual rainfall and population density (right).

NHESSD
3, 2777–2809, 2015

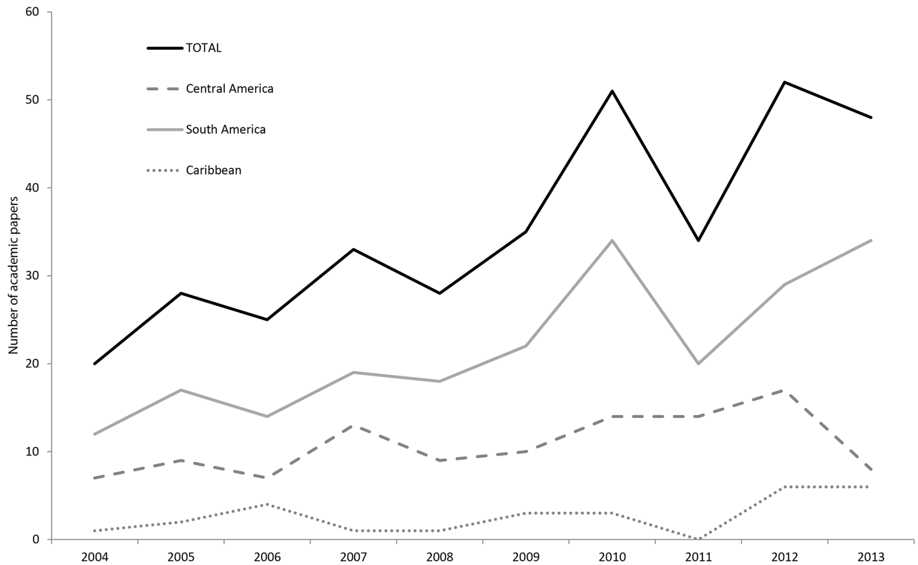

Figure 11. Scientific papers on landslides (Web of Science databases) annual distribution of all countries with recorded fatal landslides.

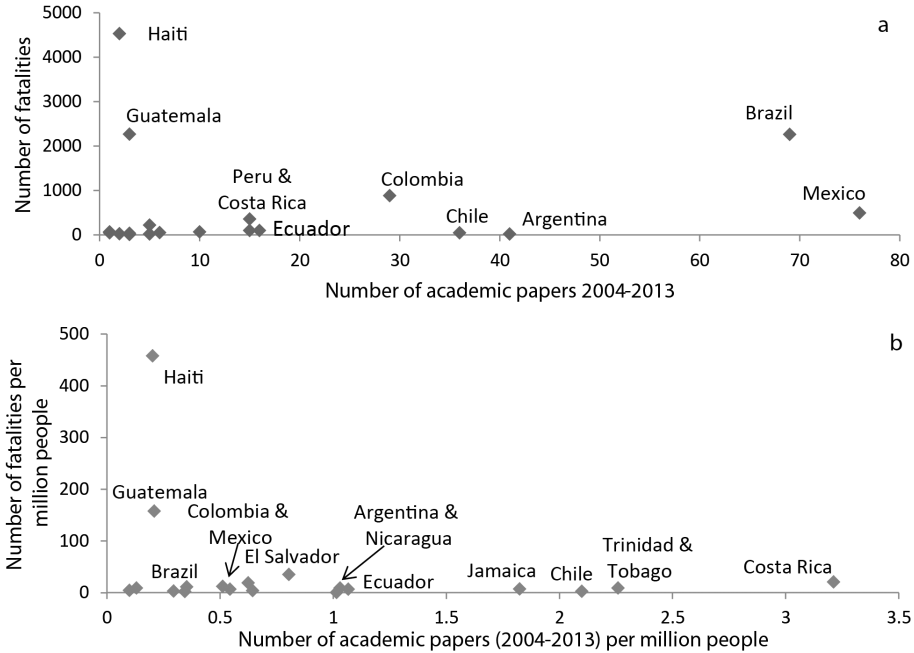

Figure 12. (a) Comparison of fatalities caused by landslides and scientific research illustrated by total number of papers (Web of Science databases) for the 2004–2013 period per country; **(b)** same indicators normalized by 2010 country population.

NHESSD
3, 2777–2809, 2015

Regional trends and controlling factors of fatal landslides

S. A. Sepúlveda and D. N. Petley