Regional Trends and Controlling Factors of Fatal Landslides in Latin America and the Caribbean

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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 11631 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, mainly 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 been previously considered. In the latter ~~ose~~ 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. However, the study is performed at a continental scale for a ten year period, thus the size of the dataset is limited and the results are not conclusive for the long term.

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 precise~~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 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, such as "deslizamiento", "deslave", "flujo", "avalancha", "desprendimiento", "aluvión", among others.~~.~~ 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, 2011b).
- 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).

- 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 most ~~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 11631 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). In fact, ~~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 heavy rainfall, from which ~~(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) episodes (Fig. 3), mainly in Central America and 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 of the frequency curve 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 some 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 fatality 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 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.~~ However, at a local scale, the geology is likely to be a key factor determining the occurrence of landslides. Because of the coarse scale of our study and of the data used here, no further analysis was undertaken.

As commented before, most of the landslides of the database were triggered by heavy rainfall, and to a lesser extent by earthquakes. Fig. 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 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 of total fatalities per country during the studied period with other socio-economic factors (Appendix 1), 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 tendency ~~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, possibly due to the complexity of the landslide phenomena that cannot be directly related to single societal indexes such these at this scale.

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 first order ~~primary~~ controlling factors of fatality-inducing landslides in the study region.

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

As noted by Petley (2012b) with examples in Hong Kong and China, ~~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). Fig. 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 populations 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.

The original dataset in English included about 95% of the total identified fatal landslide cases, showing that coverage in English is reasonably good for this sort of studies. It is not clear if this would remain for not fatal cases that are not frequently covered by the media. The use of Spanish terms to enhance the dataset was of limited value, adding generally small events with few casualties and often in small countries, such as Ecuador, that might not have as good coverage by global media in English as others. Nevertheless, the search in Spanish was not done systematically during the whole studied period as in English, but was performed at the end of the period, with higher number of cases for the last three or four years, possibly due to the deletion of older web pages. This factor, along with the absence of other important languages spoken in the continent such as Portuguese, may have precluded an optimum coverage of all cases.

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 under-sampled 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.

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 the World Bank ~~is~~ approach hazard is assessed by multiplying a number of factors, such as precipitation and seismic hazard. Thus in 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.

4.4 The role of research in disaster prevention

Even though no simple and direct link between research and landslide impact can be concluded, as other factors such as research quality and lag times or incapacity to apply research results in disaster prevention should be considered - as well as other important processes including people education - our analysis reinforce the idea that research can play a significant role of reducing the losses from landslides. Future work should explore in depth what factors or research and its communication (e.g. type of study, type of publication) may have a stronger impact in disaster prevention. It also should take into account the potential impact of unpublished reports, usually issued by national geological services or emergency offices, or articles in local congress proceedings, as local scientists out of academia do not tend to publish in journals in this region.

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 11631 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 Nino 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 pre-requisite if a meaningful reduction in landslide losses is to be achieved.

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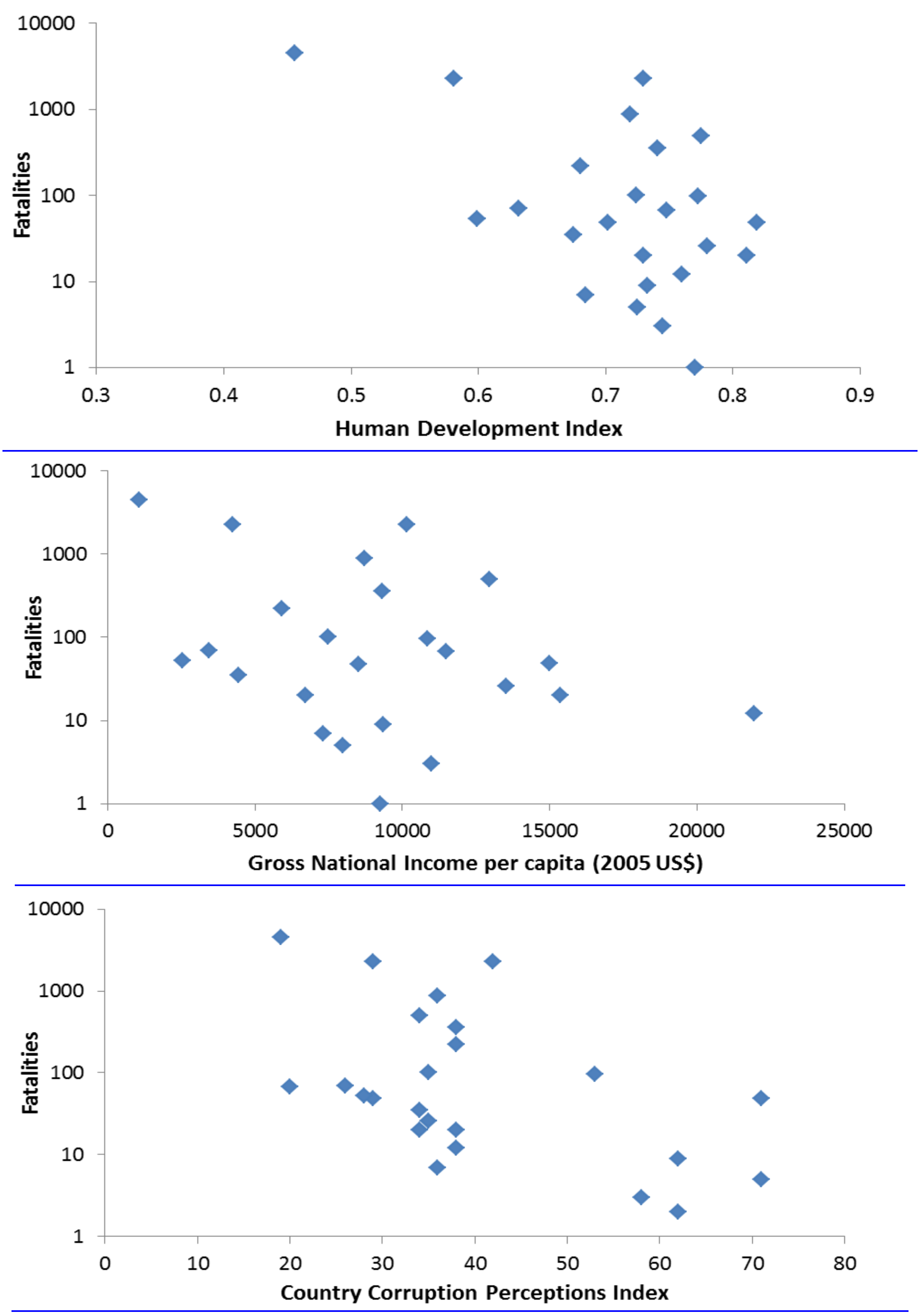
Table 1. Number of fatal landslides and fatalities for each country with positive cases.

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 & 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**	**11631**

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/km2)[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	9,896.4	356.6	2
Jamaica	2,741.5	249.4	5
Puerto Rico	3,709.7	418.0	14
St Lucia	177.4	329.1	0
St. Vincent & the Grenadines	109.3	281.7	0
Trinidad and Tobago	1,328.1	258.9	3
CENTRAL AMERICA			
Costa Rica	4,669.7	91.4	15
El Salvador	6,218.2	295.5	5
Guatemala	14,341.6	131.7	3
Honduras	7,621.2	68.0	1
Mexico	117,886.4	60.2	76
Nicaragua	5,822.2	44.8	6
Panama	3,678.1	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**



Appendix 1. Relationship between fatalities induced by landslides and societal indexes of Human Development, Gross National Income and Country Corruption.

Corrected Figures:

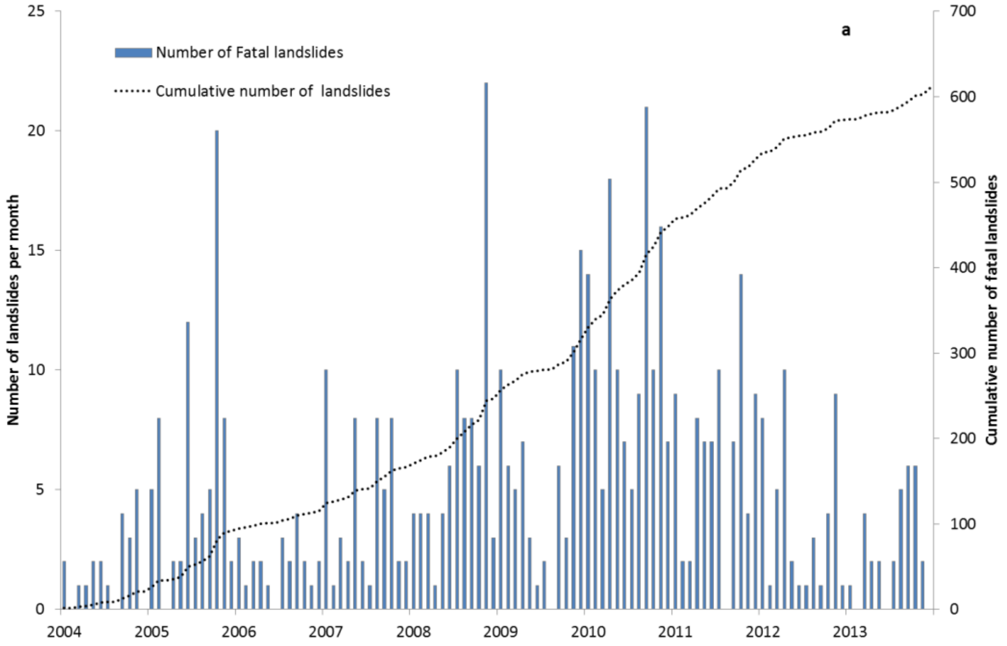


Fig 1a

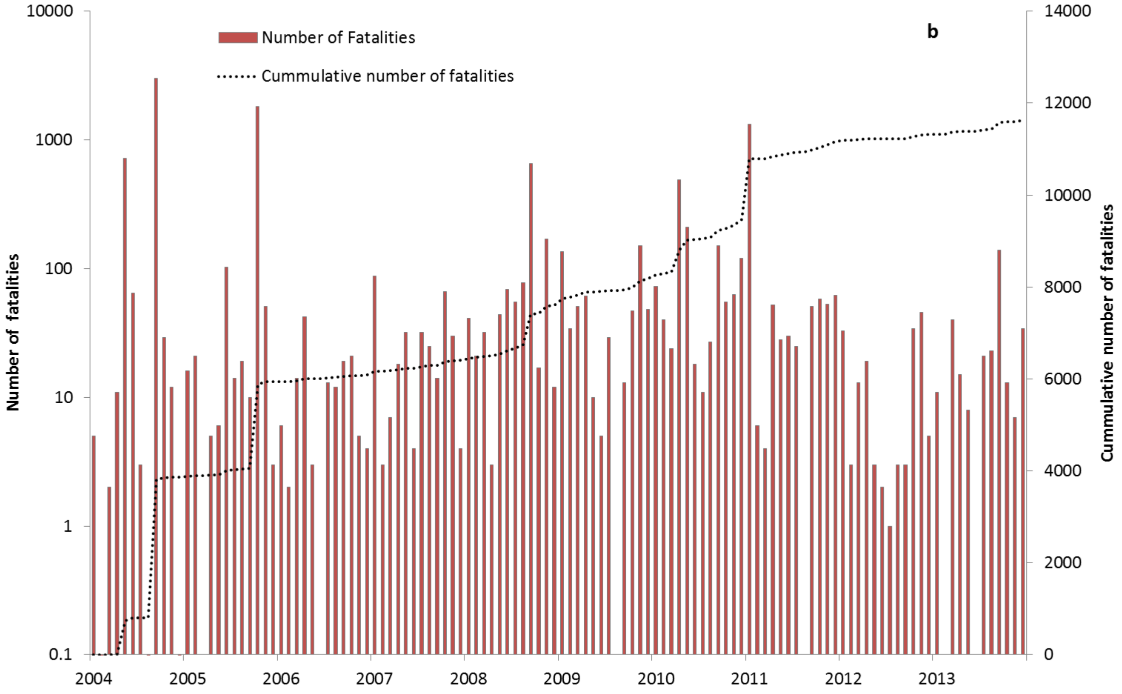


Fig 1b

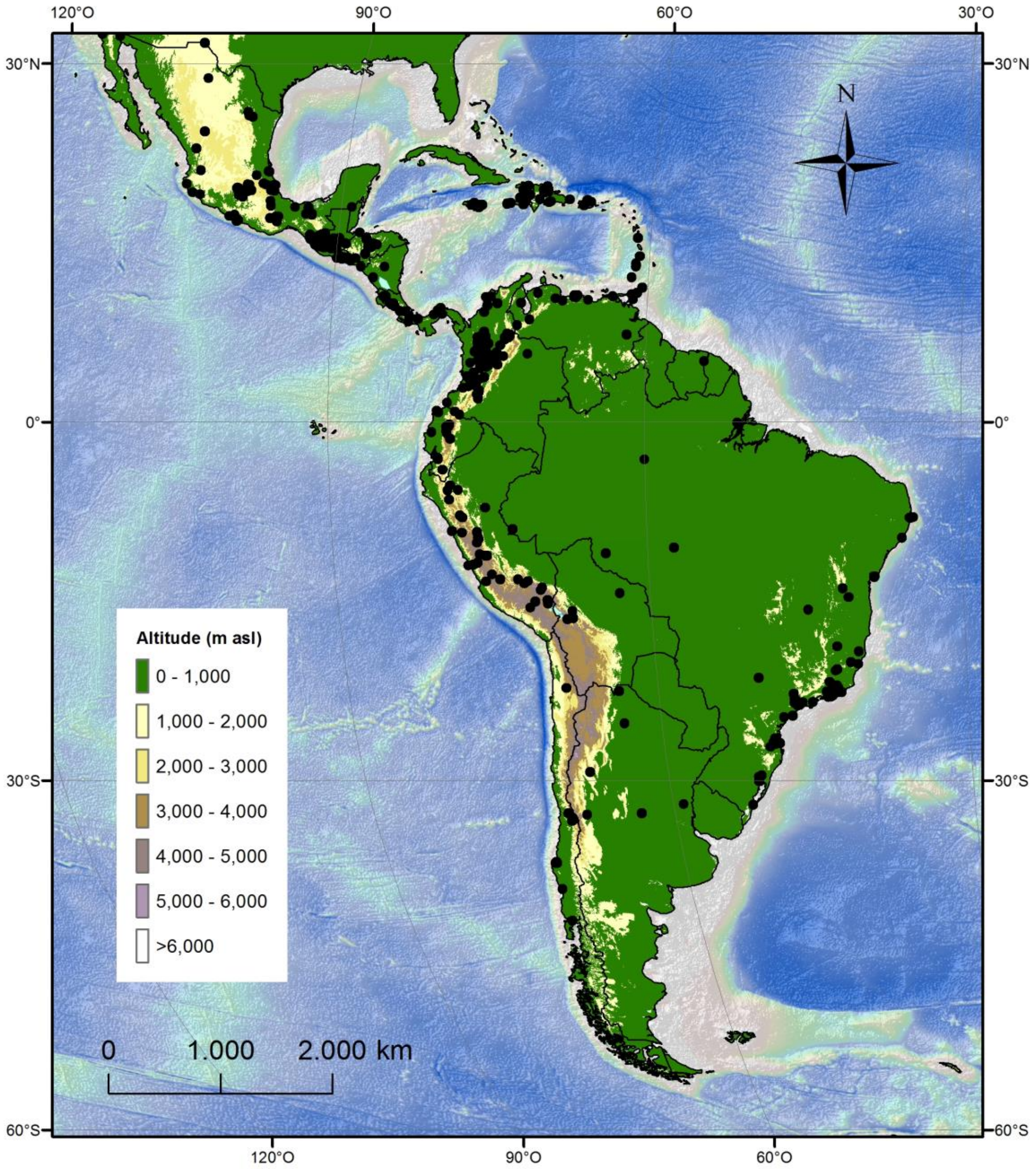

120°O
90°O
60°O
30°O
30°N
0°
30°S
60°S
120°O
90°O
60°O
N
Altitude (m asl)
0 - 1,000
1,000 - 2,000
2,000 - 3,000
3,000 - 4,000
4,000 - 5,000
5,000 - 6,000
>6,000
0
1.000
2.000 km

Fig 2

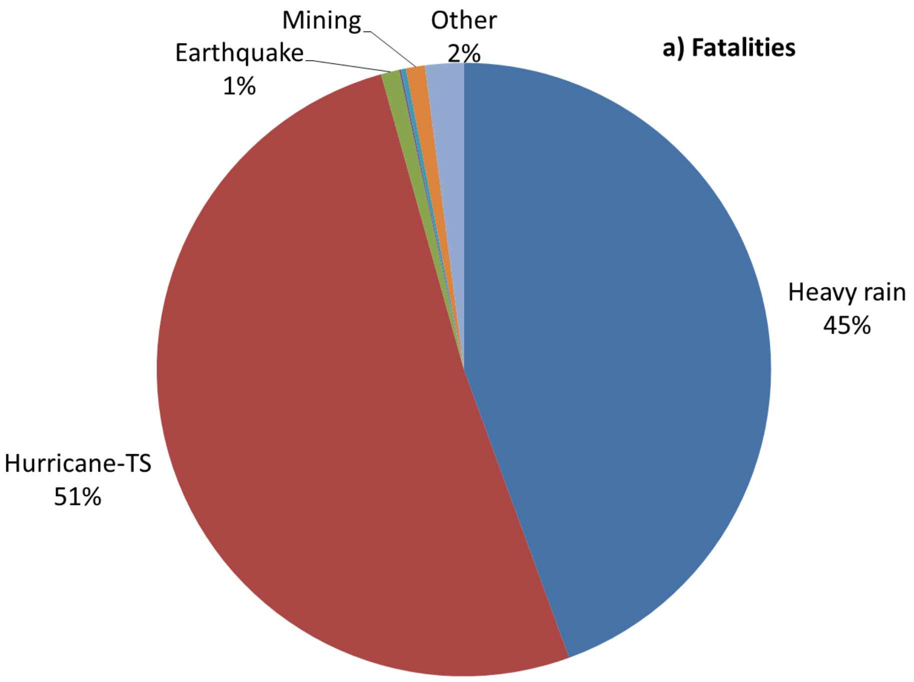

a) Fatalities
Mining
Other
2%
Earthquake
1%
Heavy rain
45%
Hurricane-TS
51%

Fig 3a

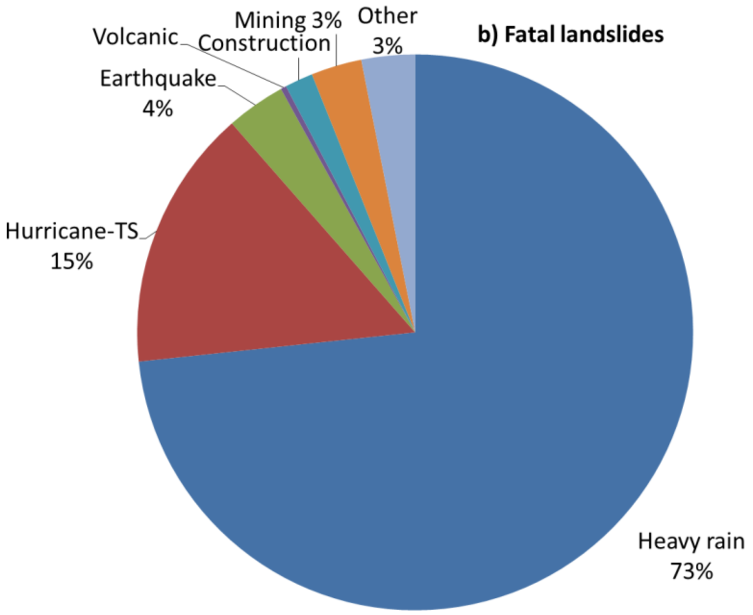

b) Fatal landslides
Mining 3%
Other
3%
Volcanic
Construction
Earthquake
4%
Hurricane-TS
15%
Heavy rain
73%

Fig 3b

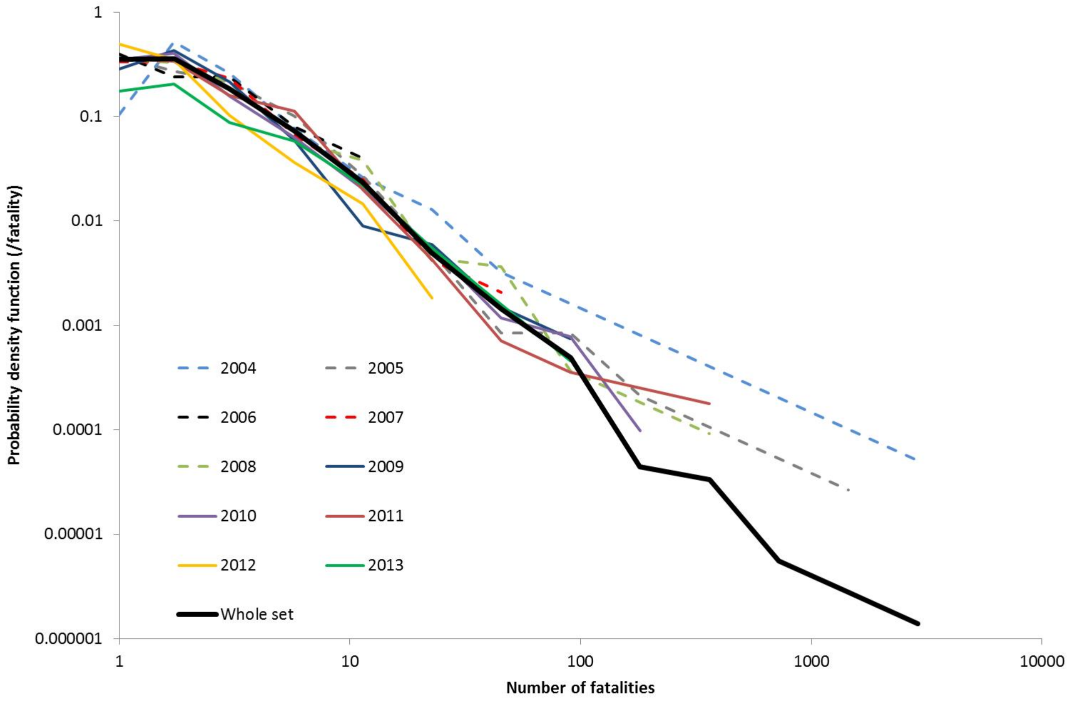

Probability density function (/fatality)
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
Number of fatalities
1
10
100
1000
10000
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Whole set

Fig 4

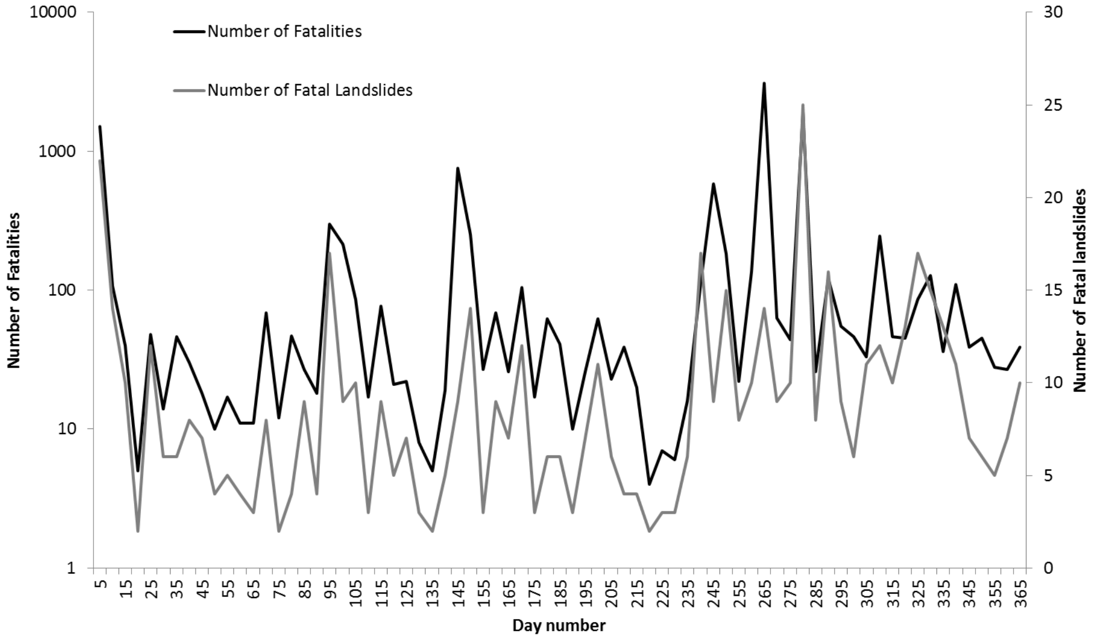

Number of Fatalities
Number of Fatal Landslides
10000
1000
100
10
1
30
25
20
15
10
5
0
Number of Fatal landslides
Day number
5
15
25
35
45
55
65
75
85
95
105
115
125
135
145
155
165
175
185
195
205
215
225
235
245
255
265
275
285
295
305
315
325
335
345
355
365

Fig 5

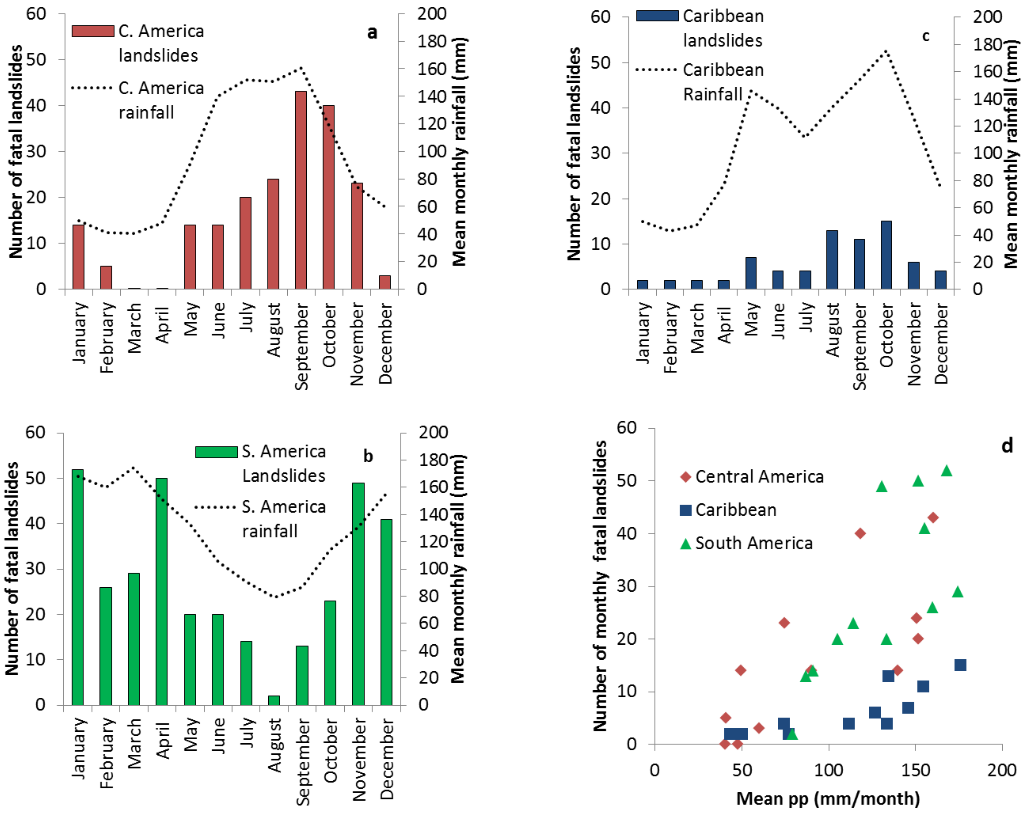

a
C. America landslides
C. America rainfall
Number of fatal landslides
Mean monthly rainfall (mm)
c
Caribbean landslides
Caribbean Rainfall
b
S. America Landslides
S. America rainfall
d
Central America
Caribbean
South America
Number of monthly fatal landslides
Mean pp (mm/month)
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
January
February
March
April
May
June
July
August
September
October
November
December

Fig 6

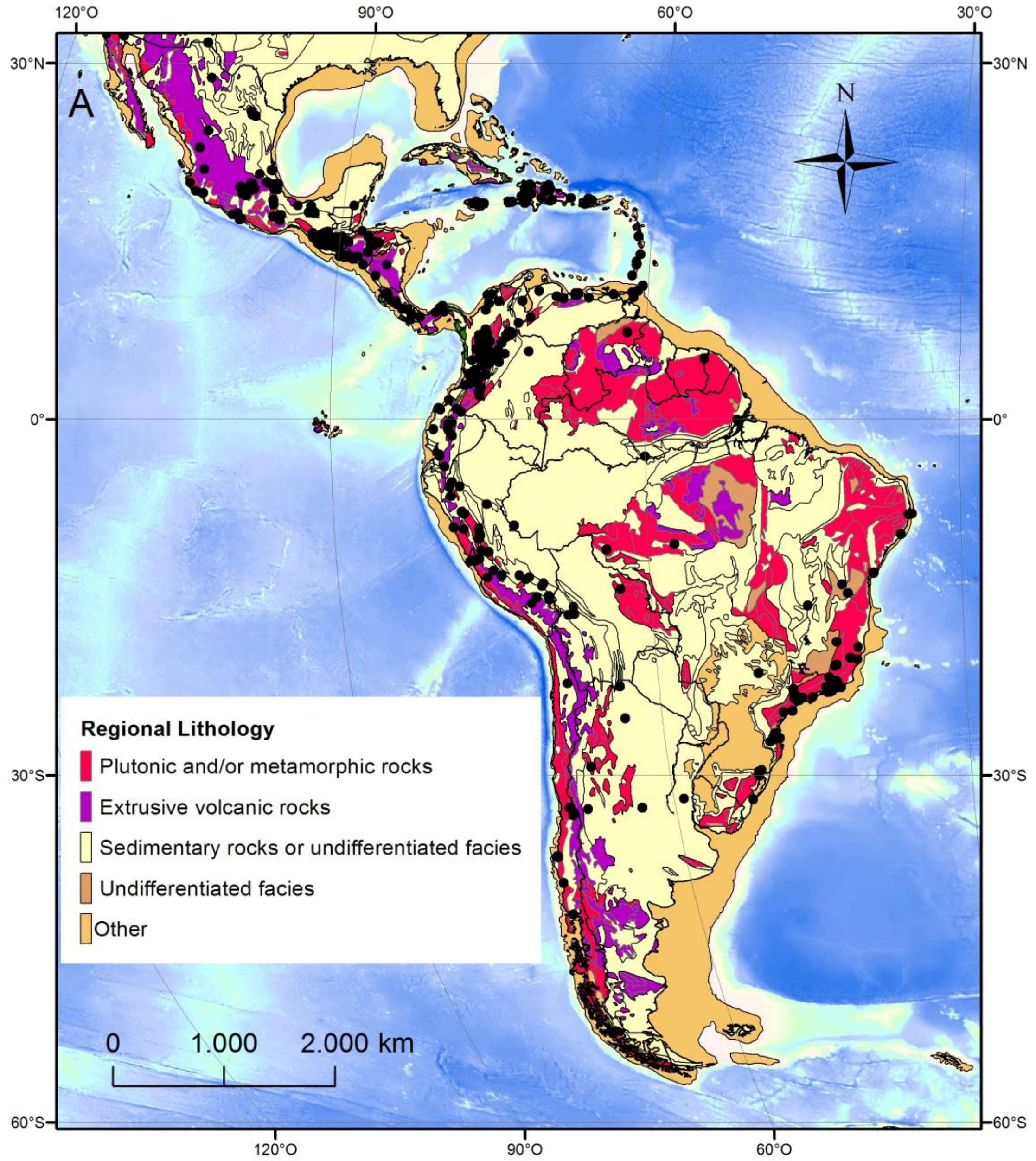

120°O
90°O
60°O
30°O
30°N
0°
30°S
60°S
A
N
Regional Lithology
Plutonic and/or metamorphic rocks
Extrusive volcanic rocks
Sedimentary rocks or undifferentiated facies
Undifferentiated facies
Other
0
1.000
2.000 km
120°O
90°O
60°O

Fig 7a

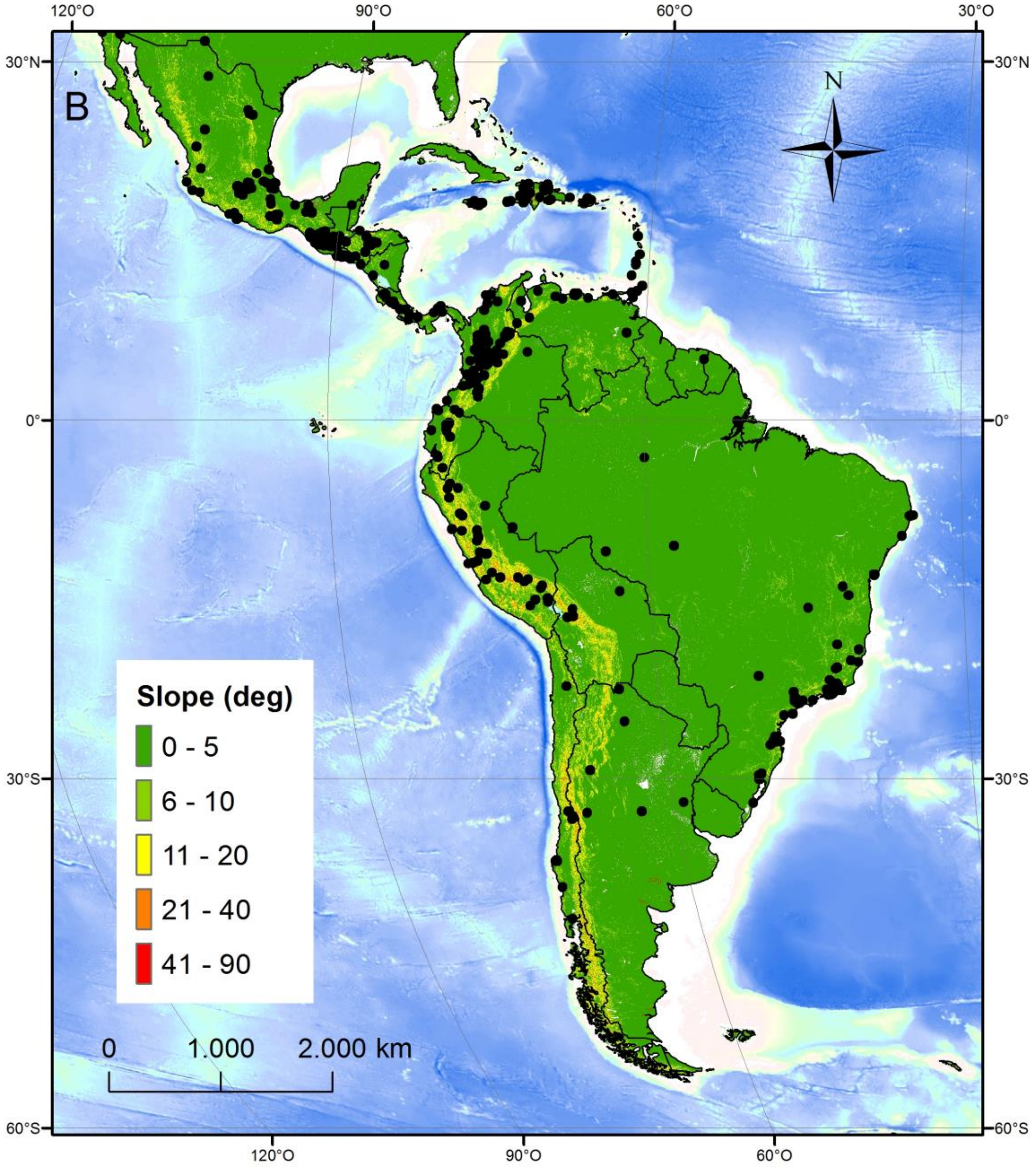

B
120°O
90°O
60°O
30°O
30°N
0°
30°S
60°S
N
Slope (deg)
0 - 5
6 - 10
11 - 20
21 - 40
41 - 90
0
1.000
2.000 km

Fig 7b

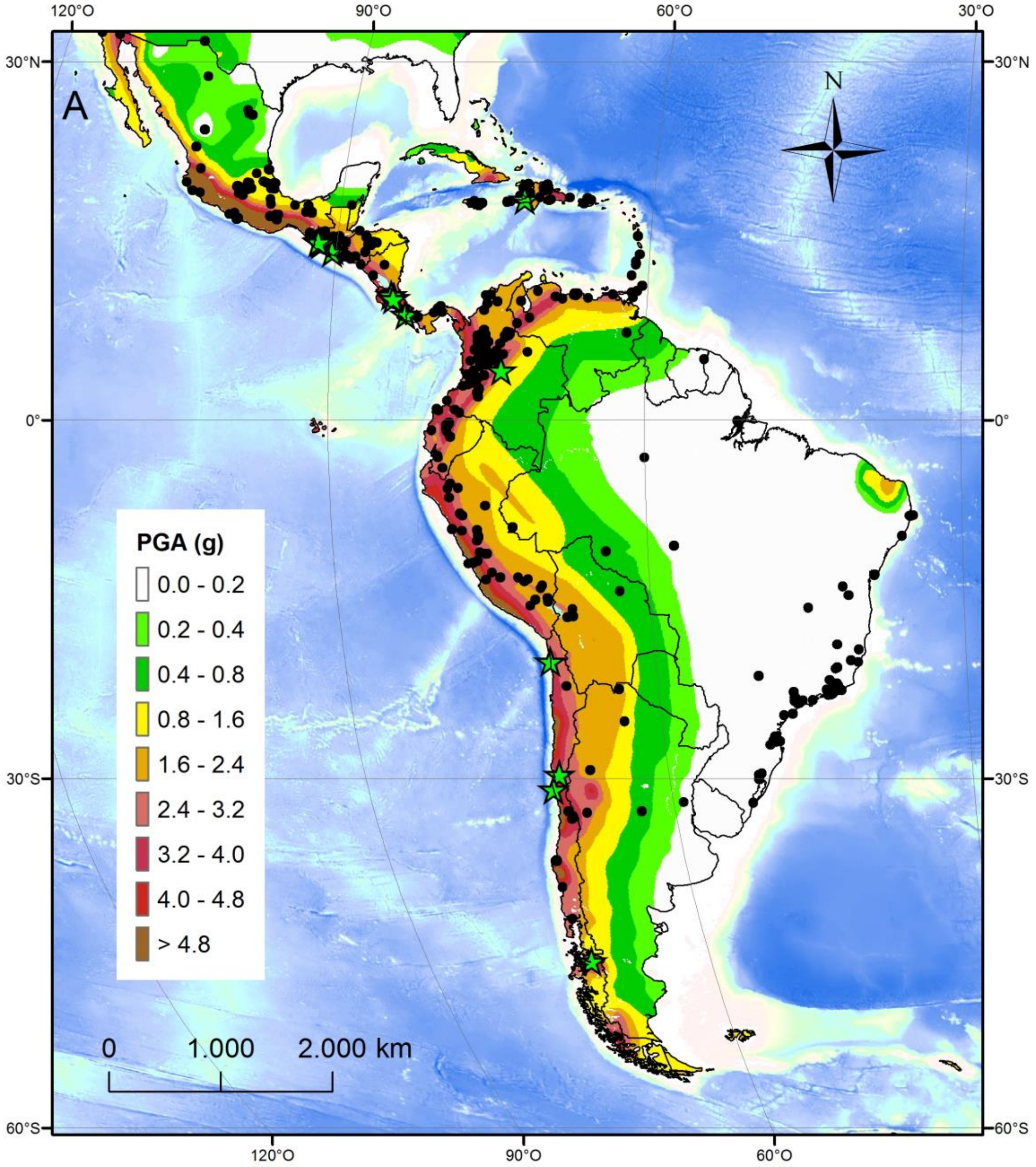

120°O
90°O
60°O
30°O
30°N
0°
30°S
60°S
A
N
PGA (g)
0.0 - 0.2
0.2 - 0.4
0.4 - 0.8
0.8 - 1.6
1.6 - 2.4
2.4 - 3.2
3.2 - 4.0
4.0 - 4.8
> 4.8
0
1.000
2.000 km
120°O
90°O
60°O

Fig 8a

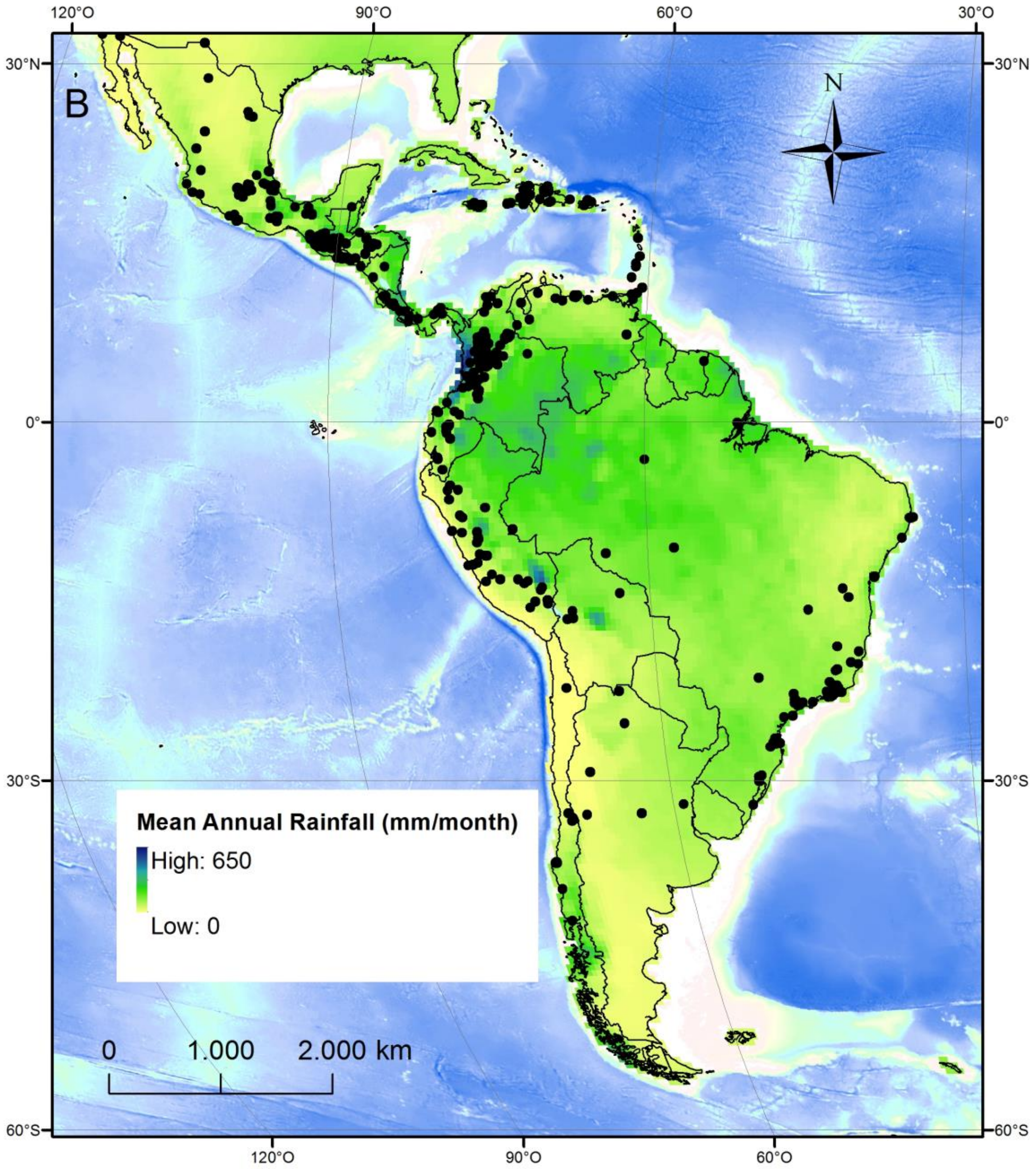

120°O
90°O
60°O
30°O
30°N
B
N
0°
30°S
60°S
Mean Annual Rainfall (mm/month)
High: 650
Low: 0
0
1.000
2.000 km
120°O
90°O
60°O

Fig 8b

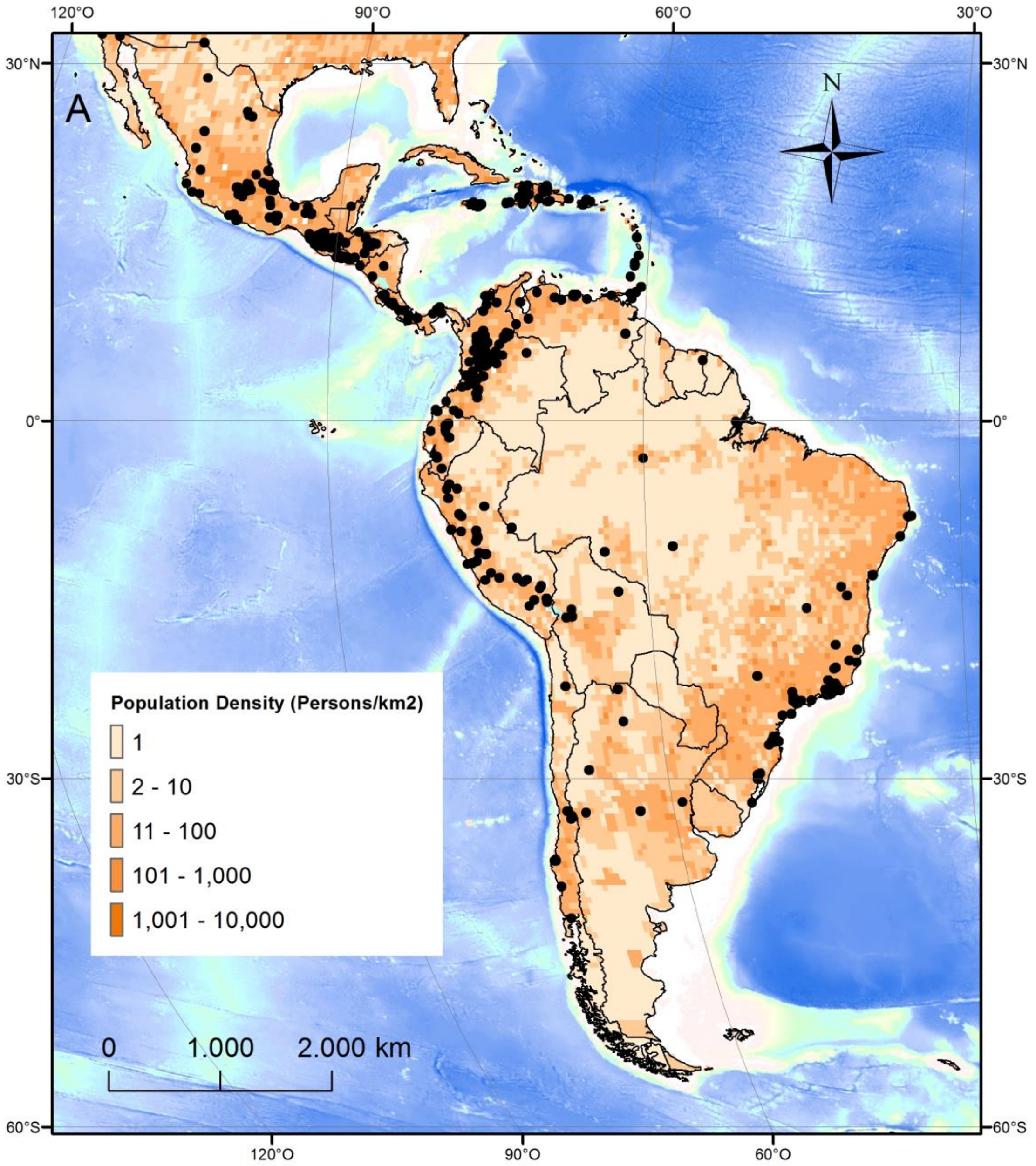

120°O
90°O
60°O
30°O
30°N
0°
30°S
60°S
120°O
90°O
60°O
A
N
Population Density (Persons/km2)
1
2 - 10
11 - 100
101 - 1,000
1,001 - 10,000
0
1.000
2.000 km

Fig 9a

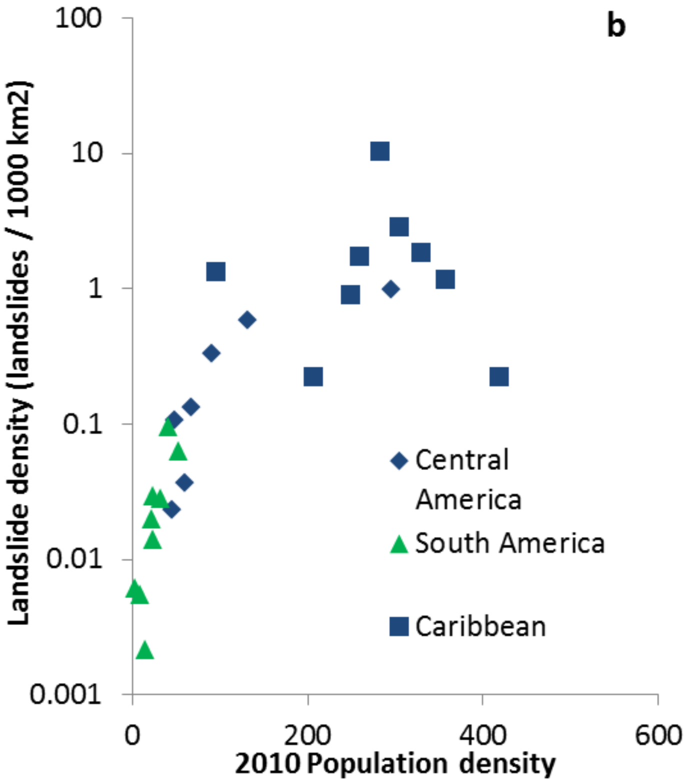

b
Landslide density (landslides / 1000 km2)
100
10
1
0.1
0.01
0.001
0
200
400
600
2010 Population density
◆ Central America
▲ South America
■ Caribbean

Fig 9b

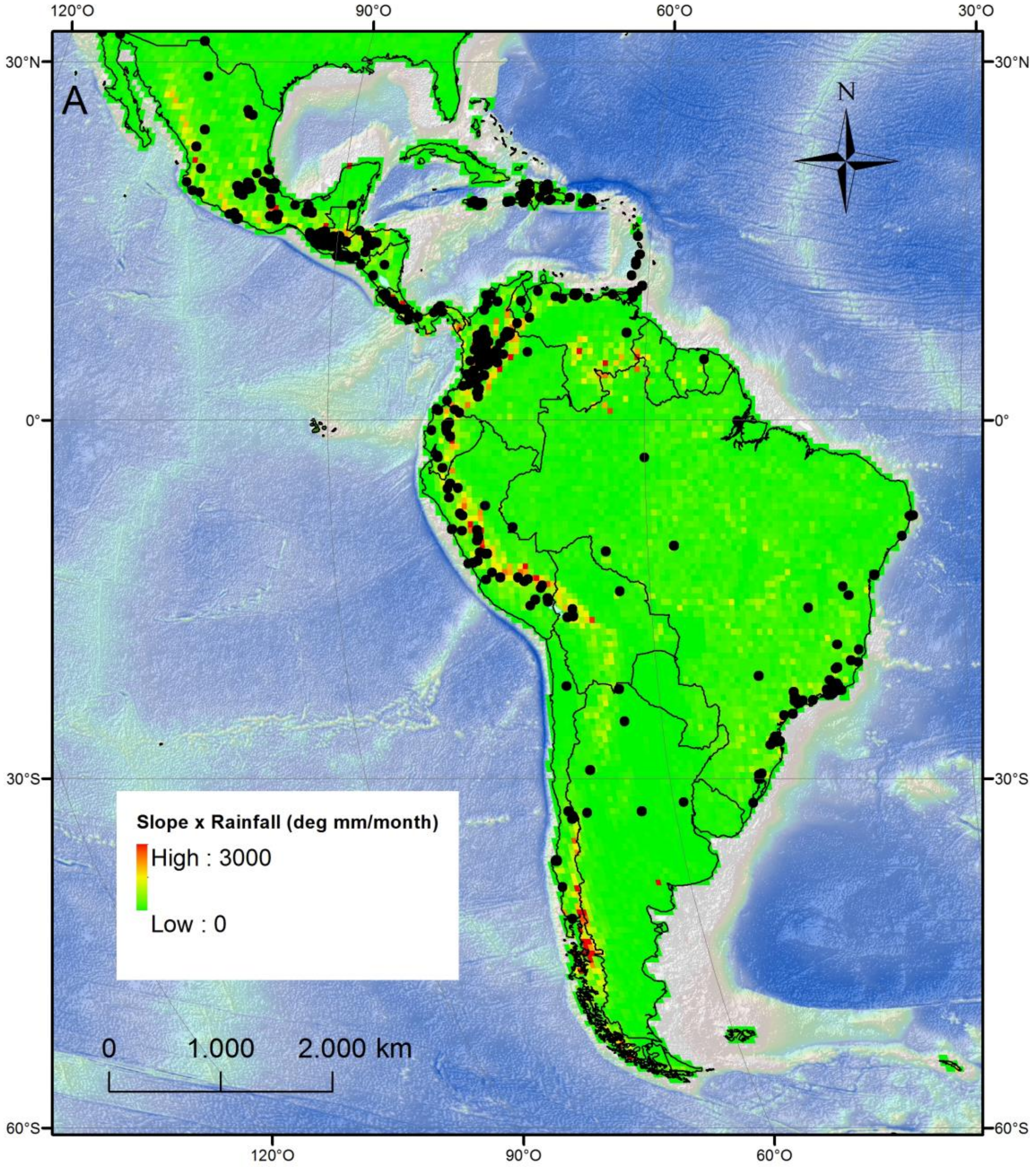

120°O
90°O
60°O
30°O
30°N
0°
30°S
60°S
A
N
Slope x Rainfall (deg mm/month)
High : 3000
Low : 0
0
1.000
2.000 km

Fig 10a

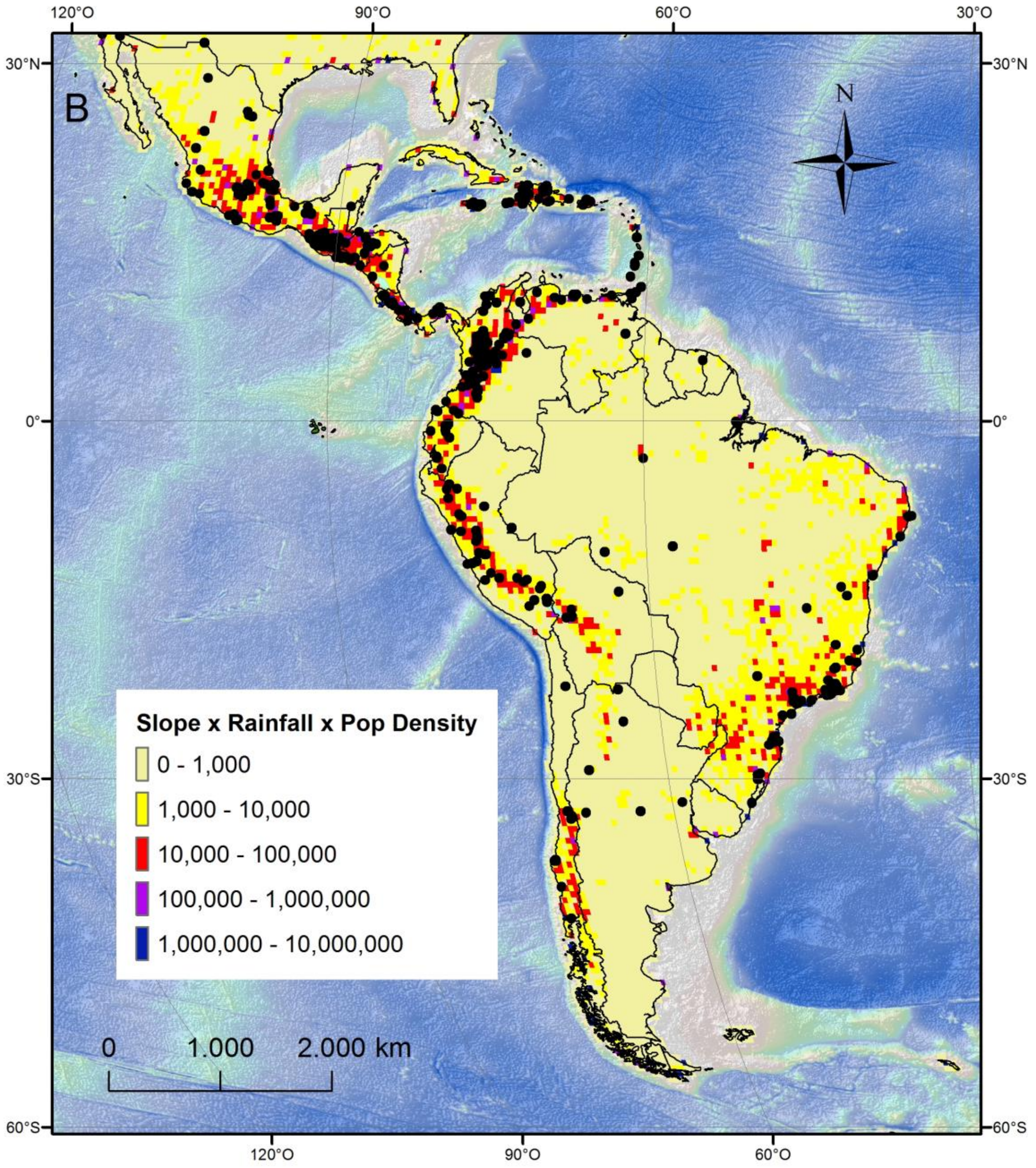

120°O
90°O
60°O
30°O
30°N
0°
30°S
60°S
B
N
Slope x Rainfall x Pop Density
0 - 1,000
1,000 - 10,000
10,000 - 100,000
100,000 - 1,000,000
1,000,000 - 10,000,000
0
1.000
2.000 km
120°O
90°O
60°O

Fig 10b

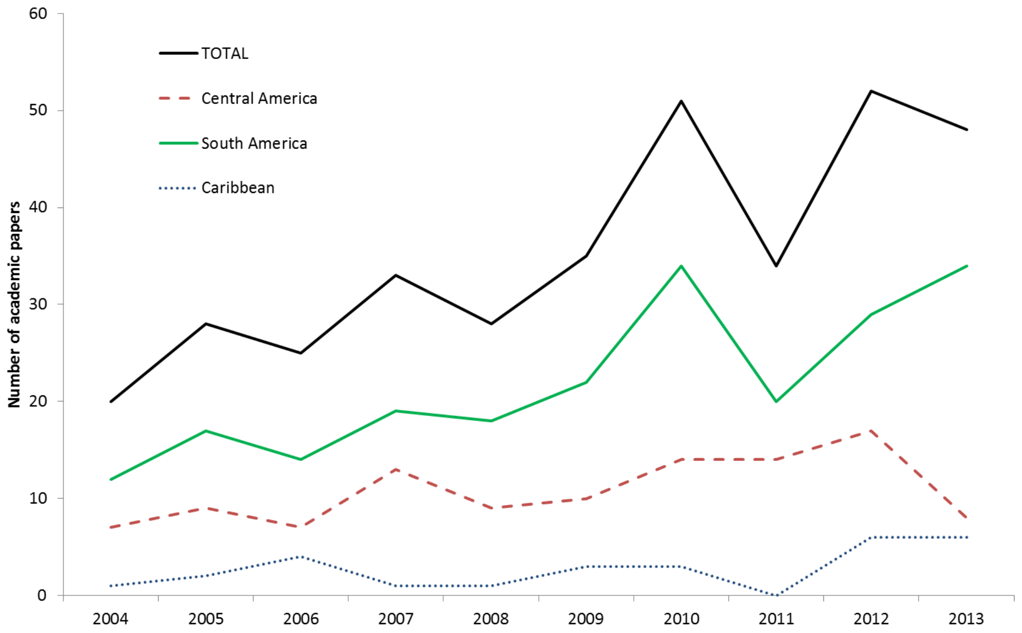

TOTAL
Central America
South America
Caribbean
Number of academic papers
0
10
20
30
40
50
60
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

Fig 11

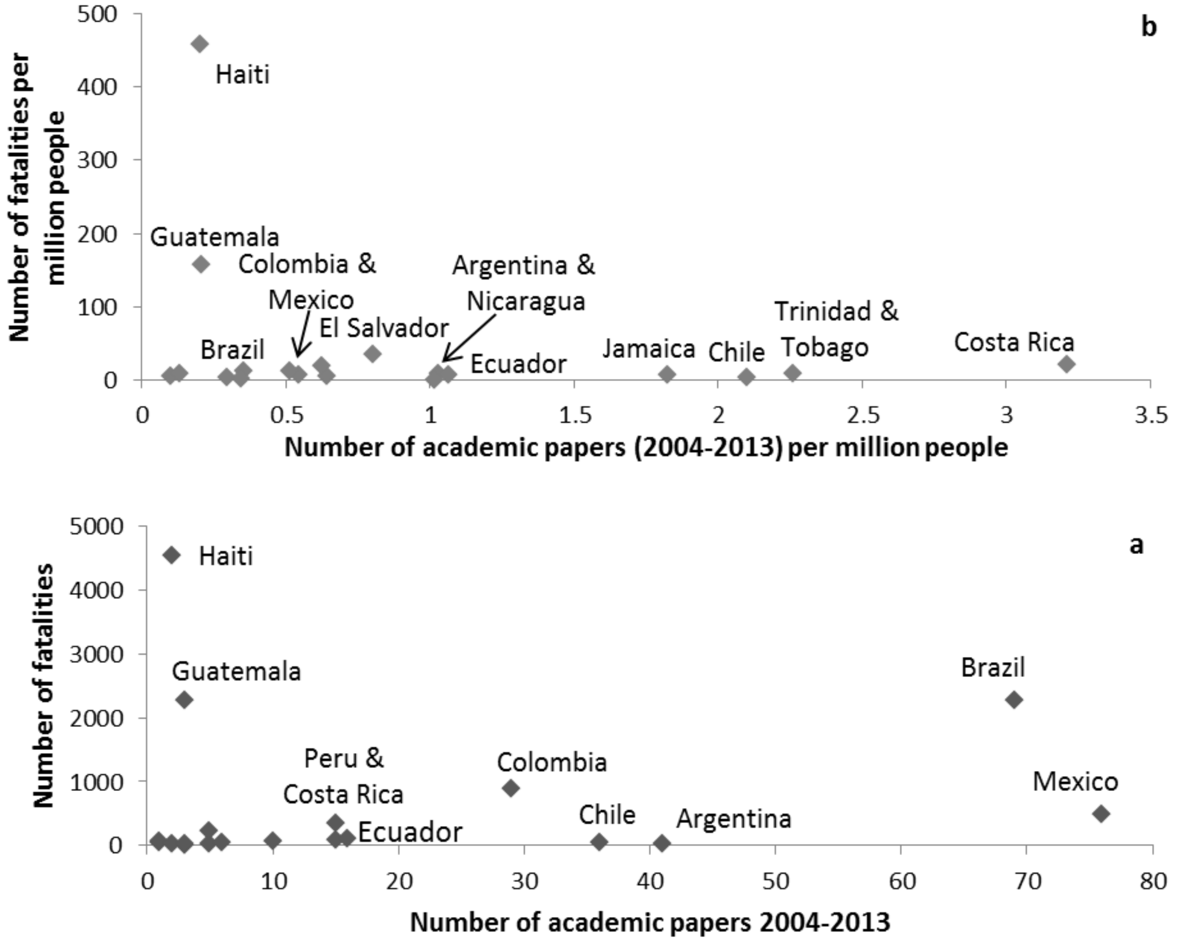

b
Number of fatalities per million people
500
400
300
200
100
0
Haiti
Guatemala
Colombia &
Mexico
El Salvador
Brazil
Argentina &
Nicaragua
Ecuador
Jamaica
Chile
Trinidad &
Tobago
Costa Rica
0
0.5
1
1.5
2
2.5
3
3.5
Number of academic papers (2004-2013) per million people
a
Number of fatalities
5000
4000
3000
2000
1000
0
Haiti
Guatemala
Peru &
Costa Rica
Ecuador
Colombia
Chile
Argentina
Brazil
Mexico
0
10
20
30
40
50
60
70
80
Number of academic papers 2004-2013

Fig 12