GLOBAL FATAL LANDSLIDE OCCURRENCE 2004 TO 2016

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Abstract

Landslides are a ubiquitous hazard in terrestrial environments with slopes, incurring human fatalities in urban settlements, along transport corridors, or at sites of rural industry. Assessment of landslide risk requires high quality landslide databases. Recently, global landslide databases have shown the extent to which landslides impact on society and identified areas most at risk. Previous global analysis has focused on rainfall-triggered landslides over short ~5 year observation periods. This paper presents spatio-temporal analysis of a global dataset of fatal non-seismic landslides, covering the period from January 2004 to December 2016. The data show that in total 55,997 people were killed in 4,862 distinct landslide events. The spatial distribution of landslides is heterogeneous, with Asia representing the dominant geographical area. There are high levels of inter-annual variation in the occurrence of landslides. Although more active years coincide with recognised patterns of regional rainfall driven by climate anomalies, climate modes (such as El Niño- Southern Oscillation) cannot yet be related to landsliding, requiring a 30+ year landslide dataset. Our analysis demonstrates that landslide occurrence triggered by human activity is increasing, in particular in relation to construction, illegal mining and hill-cutting. This supports notions that human disturbance may be more detrimental to future landslide incidence than climate.

1. Introduction

Landslides are ubiquitous in any terrestrial environment with slopes, driven by tectonic (*e.g.* Bennett *et al.*, 2016), climatic (*e.g.* Moreiras, 2005) and/or human (Petley *et al.*, 2007) activities. Losses (fatalities, physical asset damage and economic costs) occur when people and their associated structures are exposed to landslides. The magnitude of the impact depends on the number of exposed elements and their associated vulnerabilities; the consequences of the impacts; and the intensity of the landslide event (Glade and Crozier, 2005). A landslide event may include more than one slope failure triggered by the same phenomenon (e.g. a rainstorm). Interest in quantifying landslide risk has developed since the attempt by the International Association of Engineering Geology (IAEG) Commission on Landslides to compile a list of worldwide landslide events for the UNESCO annual summary of information on natural disasters in 1971 (UNESCO, 1973). Although incomplete, five years of records (1971-1975) recognised that landslides are a significant global hazard, with *c.*14% of total casualties from natural hazards being attributed to slope failure (Varnes and IAEG Commission on Landslides, 1984). Since, there has been a growing interest in landslide hazard and risk assessment (Wu *et al.*, 2015).

Key elements of the assessment of landslide risk are coherent, high quality landslide databases and inventories (van Western *et al*., 2008; Van Den Eeckhaut and Hervás, 2012; Taylor *et al.*, 2015). Inventories provide systematically compiled lists of landslide events that have occurred over a specific spatial scale (*e.g.* within a nation) within a set period of time, or that result from a single, catastrophic triggering event (Hervás and Bobrowsky, 2009). Databases organise inventory information so that it is structured and searchable. Spatio-temporal analysis of global records of landslides have demonstrated the extent to which landslides impact on society, and have identified geographical regions and countries most exposed (Petley, 2012). Several different global databases are actively maintained (e.g. the EM-DAT International Disaster Database, The NASA Global Landslide Catalogue, and the Global Fatal Landslide Database (GLFD) on which this study is based), and their merits and limitations are discussed by Van Den Eeckhaut and Hervás (2012) and Kirschbaum *et al.* (2015). Global disaster databases are also maintained by risk reinsurers, however landslides are often included within broader categories (such as geophysical hazards or within weather-related hazards), and the majority of data are not freely available.

Relative to other natural disasters, the International Disaster Database (EM-DAT) suggests that landslides account for 4.9 % of all natural disaster events and 1.3% of all natural hazard fatalities between 1990 and 2015; 54% of these landslide events occurred in Asia (Guha-Sapir *et al.*, 2018).

However, the dedicated global landslide databases indicate that global multi-peril databases underestimate the impact of landslides on society. Petley (2012) showed that the EM-DAT database underestimated the number of fatal landslide events by ~2000% and fatalities by 430% between 2004 and 2010, whilst Kirschbaum *et al.* (2015) showed that the EM-DAT database underestimated the number of fatal landslide events by ~1400% and fatalities by 331% between 2007 and 2013. For the most-part this under-reporting is associated with the perception of landslides as a secondary hazard, with the cause of death often being recorded in connection with the primary hazard (e.g. an earthquake rather than a co-seismic landslide), rather than the actual cause of the loss.

Past studies on global landslide distribution have focused on rainfall-triggered events, recognising the importance of rainfall and climate in inhabited regions with steep slopes (Dowling and Santi, 2014; Kirschbaum *et al.*, 2012; 2015). This paper not only provides a key update on the impact of landslides worldwide, extending Petley (2012) to include landslides from 2004 to 2016, the study considers trends in landslides triggered by human activity. Thereby, adding to the discussion on climate versus human disturbance as current and future drivers of landslide incidence (Crozier, 2010).

2. The Global Fatal Landslide Database

The GFLD (formerly termed the Durham Fatal Landslide Database) has been compiled using systematic, English language based, metadata search tools that identify relevant reports of landslide activity (including all mass movements falling within the definition of Hungr *et al.* (2014) on a daily basis (Petley *et al.*, 2005; Petley, 2010; 2012). In common with other hazard databases (Tschoegl *et al.*, 2006; Taylor *et al.*, 2015), mass media reports provide a first alert for fatal landslide occurrence and impact. Reports are corroborated and data updated by source triangulation using government and aid agency reports, academic papers and personal communications, as new information becomes available. The dataset has been consistently collected and managed since 2004, following a period of methodological development between 1 September 2002 and 31 December 2003 (Petley, 2012). The approach is differentiated from that of Kirschbaum *et al.*, (2010; 2012; 2015) because: (1) only landslides that cause loss of life are included; and (2) all landslides are included, as opposed to only those triggered by rainfall. In addition, the GFLD has been compiled over a longer period. Although media reporting tends to be biased towards landslides with human casualties (Carrara *et al*., 2003), which is favourable for a database of this nature, it is recognised that the data collected is to some degree an underestimate of the number of fatal landslides, and their associated losses. Landslides that occur in remote mountain regions, or that result in a small number of fatalities, are less likely to be reported than multi-fatality landslides and/or those that occur in urban centres (Petley, 2009). Reliability of reporting is also spatially variable, based on the robustness of regional communication networks, which are considered more consistent in developed nations (Petley, 2010; Kirschbaum *et al.*, 2010), and in some cases political considerations (*e.g.* very few landslides are recorded in North Korea). The true number of fatalities may be slightly underestimated when victims die of landslide derived injuries weeks to months following the event (Petley, 2012). Furthermore, solely non-English reporting of landslides will account for some missed reporting. However, Sepúlveda and Petley (2015) compared the GFLD with an independently compiled database based on original Spanish and Portuguese language reports for Latin America, and found a difference of only 5% of total records, generally associated with landslides with small numbers of fatalities. Combined these effects may underestimate the true level of loss by up to 15% (Petley, 2012); however the methodology of collation of the GFLD is considered robust.

Since 2004, the database has been compiled to include the date of occurrence, the description of landslide location; an approximate latitude and longitude for that location; the country and geographical region (based on UN classifications, UNSD, 2018) in which the landslide occurred; the number of fatalities and injuries; and whether the event was triggered by rainfall, seismicity or another cause. Seismically triggered landslides in the database are excluded from analysis herein, because the catalogue of events is not considered complete (see Petley, 2012). These equate to 168 earthquake events and 3978 fatalities. In preparation of this paper, all landslide reports were reviewed to enhance the classification of the trigger event according to Table 1, using keyword searches in the original text describing the landslide. The description of the landslide event location may be specific to a section of road or village, or give a more general location within an administrative division (such as a county, or state). The location of all landslide events are known within political country boundaries. To estimate the spatial precision of each landslide report, location descriptions were related to spatial databases of administrative boundaries (GADM, 2017), transport network maps (Google Maps, 2018; Open Street Map, 2018), and in some cases individual landslides could be identified from satellite imagery (Google Earth, 2018; Planet Team, 2017). For administrative units such as villages or states, polygon area from GADM (2017) provided the measurement of spatial precision. For stretch of road, a polyline of the road length was created using transport network data (Open Street Map, 2018) and a 500 m buffer applied; the area of the buffer provided the precision estimate. The median spatial precision of entries is 681 km^2, with an interquartile range of 1 to 3477 km^2. A sample of the database and further information are provided in Supplementary Material.

3. Global Fatal Landslide occurrence, 2004 to 2016

The total number of fatal landslide events recorded worldwide, excluding those triggered by earthquakes, over the twelve calendar years between 2004 and 2016 (inclusive) was 4862. The majority of events (95%) involved a single slope failure. The spatial distribution of landslides (Fig. 1a and 1c) is clearly heterogeneous, with high areas of incidence in:

- Central America between Costa Rica and the South of Mexico
- The Caribbean islands.
- South America, along the Andes mountain range from Venezuela to Bolivia and to a lesser extent Chile, with another cluster of events on the east coast of Brazil around the states of Sao Paolo and Rio de Janeiro.
- East Africa, around the borders between Tanzania, Rwanda, Burundi, Kenya, Uganda and Democratic Republic of the Congo.
- Asia, which is the site of the highest number of events (75% of landslides). Substantial numbers of landslides occur along the Himalayan Arc, in states across India and southeast China, as well as high numbers in the neighbouring countries of

Laos, Bangladesh and Myanmar, and southwards on islands that form Indonesia and the Philippines.

- There are smaller clusters in Turkey and Iran, as well as in the European Alps.

Fatal landslide events cluster around cities (Fig. 1c) and occur most frequently in countries with lower Gross National Income (GNI, Fig. 1c) at locations known to be susceptible to landslides, based on the analysis of physical characteristics of the environment (see Hong *et al.*, 2007; Stanley and Kirschbaum, 2017). Textual analysis of landslide reports shows many events occurred in mines or quarries (423 landslides), and 568 landslides in the dataset occurred on roads. Relative poverty is also emphasised in reporting: the term ‘slum’ is explicitly used to describe the impacted community 29 times, while broader terms to indicate relative poverty are used 267 times within landslide reports. These observations support previous research that fatal landslides are most prevalent in densely occupied urban centres (Alexander, 1989; Anderson, 1992; Petley, 2009), along roads (Hearn, 2011; Lee *et al.*, 2018), and at sites rich in natural resources (Zou *et al.*, 2018). In common with other natural hazards, the poor are disproportionately affected by landslides (Hallegatte *et al.*, 2016).

Fig. 2 shows landslide occurrence in pentads, smoothed with a 25-day (*i.e.* five pentad) moving average. The most landslide events in a single pentad was 48, in early October 2009; of these 45 were triggered in a single day (8^{th} October 2009) by Typhoon Parma in the Philippines. Rainfall is the leading trigger of landslides. The majority of non-seismic fatal landslide events (2004-2016) in the database were triggered by rainfall (79%). Fig. 3a shows landslide events triggered by rainfall in pentads, compared with the complete non-seismic landslide event dataset. The data series are strongly correlated (R, 0.933, *p-value*, 0), indicating that rainfall triggered landslides explain 93% of the variance of the complete dataset. Fig. 3b shows landslide events that were not triggered by rainfall, and where the trigger is known (*e.g*. mining). We term these events “non-seismic non-rainfall triggered (NSNR) landslides” herein. These landslide events constitute 16% of the complete dataset and present a different pattern through time when compared with rainfall-triggered landslide events.

There is a notable increase in the number of landslide events with NSNR triggers from about 2006, which we ascribe to improved event capture.

The rainfall-triggered landslide data in Fig. 3a (and the complete landslide series, Fig. 2) contain a strong seasonal pattern of landslide occurrence through the annual cycle, as noted by Petley (2012). Autocorrelation measures the linear relationship between lagged values of a time series. The autocorrelation of the rainfall-triggered pentad landslides series (Fig. S1) shows the correlation coefficient between the original series and a lagged version of the series, where the series lags between 1 to 948 pentads (5 days to ~13 years). The autocorrelation oscillates around 73.5 lags (pentads), equating to one calendar year. This pattern is indicative of annual seasonality in the data. Conversely, the autocorrelation of the NSNR landslides pentad series (Fig. S2) does not contain this pattern and the correlation coefficients are generally weak. This indicates that there is no seasonal pattern in the NSNR landslide series, which is to be expected in events that are not triggered by meteorological processes.

3.1. Seasonality

Landslide event occurrence peaks in the northern hemisphere summer, and there is notable inter-annual variation, both in the size and shape of the annual cycle. Seasonality in the global series (Fig. 2 and 3a) is associated with the annual cycle of rainfall-triggered landslides in South, South East and East Asia, and South and Central America (Fig. 4). Combined, these geographical regions contain 88% of all rainfall-triggered landslide events and account for 96% of variance in the global seasonal cycle (Table B1). There is a correlation between the mean monthly rainfall (data from GPCC, 2018; Xie *et al.*, 2013) and landslide series, for four of five regions (Fig. 5 and Table 2), reflecting the triggering effect of seasonal rainfall. However, the strength of relationship between seasonal patterns of rainfall and the seasonal pattern of landslide events is variable between regions. The pattern is strongest in East Asia and South Asia. This corroborates Petley (2012) who identified the strong relationship between landslide occurrence and seasonal rainfall from a shorter period of data (2004 to 2009).

Seasonal rainfall in East and South Asia is associated with the onset and withdrawal of the Asian monsoon (*e.g.* Webster, *et al.* 1998), delivered by the seasonal reversing of winds to flow from ocean to land in the summer months, resulting in the majority of annual rainfall occurring between June and September (Turner and Annamalai, 2012). In South Asia, landslide incidence increases in Nepal, India, Bangladesh, Bhutan and northern Pakistan during the summer monsoon. India and Nepal contribute 16% and 10% respectively of all rainfall-triggered landslide events in the global dataset; of these 77% and 93% occurred during the summer monsoon, meaning 21% of all rainfall-triggered landslide events globally were triggered by seasonal monsoon rainfall in India and Nepal. In East Asia, tropical cyclones extend the length of the rainfall season: 109 landslide events were triggered by typhoons between April and October in China, Japan and South Korea, representing 16% of rainfall-triggered landslide events in East Asia, and 3% of global rainfall-triggered landslide events. The East Asia landslide record is dominated by events in China (81%, 503 landslides), of which 409 landslide events were triggered during the summer monsoon rainfall season. China alone contributes 15% of all global rainfall-triggered landslide events, although the pattern is heterogeneous.

Although, the seasonal landslide series for Central and South America do not explain much variance in the global seasonal landslide cycle (because of the comparatively low number of landslides), there is strong correlation between patterns of landslides in the region and patterns of rainfall (Table 2). Central America and parts of the Caribbean experience a summer rainy season between May and October, associated with the position of the Inter-Tropical Convergence Zone (ITCZ; Garcia *et al.*, 2009). The season is bimodal, with peaks in rainfall on either side of a midsummer drought, between late June to August (Magaña *et al.*, 1999). The season is enhanced by the Atlantic basin hurricane season from 1 June to 30 November (NOAA, 2018a). The pattern of landslides reflects these rainfall drivers. South America spans ~70º of latitude leading to local variability in climate (Sepúlveda and Petley, 2015). The peak annual rainfall for the continent as a whole occurs during the period from December through to February, delivered by the South American

Monsoon System (SAMS), which is driven by the position of the ITCZ to the south of the equator (Garcia *et al*., 2009). However, in parts of south-eastern Brazil, where there is a prevalence for fatal landslides (Fig. 1), the rainy season extends into March (Rao and Hada, 1990). In northern Peru, rainfall peaks between April and June in the west, and is bimodal in the east, with peaks in April and December (Espinoza *et al.*, 2009). Colombia's meteorology is particularly complex due to the convergence of the Equatorial Mid-tropospheric Easterly Jet (EMEJ) and the Choco Jet; the resulting rainfall distribution is bimodal, with peaks in April-June and August-September, depending on precise location and the choice of rainfall data and model (Sierra *et al.*, 2015). Most rainfall-triggered fatal landslide events in South America occur in Brazil (37%) and Colombia (32%), most notably in south-eastern Brazil and central Colombia, and this is evident in the distribution of annual rainfall and landslide occurrence (Fig. 5d).

The weak relationship between rainfall and landslides in South East Asia reflects the complex weather systems operating in the region. Most landslide events occurred in the Philippines (46%) and Indonesia (32%). Typhoons caused 22% of rainfall-triggered landslide events in the region, and 5% globally; most typhoon-triggered landslide events occurred in July through to October (75%), in line with the main tropical cyclone season. In the Philippines, 42% of rainfall-triggered landslide events were caused by Typhoons, whilst the equivalent value for Vietnam was 22%, although of a much lower total. The pattern of monsoon rainfall in Indonesia and the Philippines varies by geographical location. In the west of the Philippines, summer monsoon occurs between June and October, while in the east, the winter monsoon occurs between October and March (Kubota *et al.*, 2017). This pattern is evident in the distribution of rainfall-triggered landslides in the Philippines (Fig. 1a). The onset and termination of the monsoon in Indonesia varies from September to June in north Sumatra and late November to late May in east Java (Naylor *et al.*, 2007). Consequently, 72% of rainfall-triggered landslide events occur between November and April, when the majority of Indonesia is experiencing monsoon rainfall. The peak in landslide activity relative to rainfall in August to October in South East Asia (Fig. 5b) is mainly due to the localised typhoon rainfall not captured in the regional rainfall average.

3.2. Medium term trend in landslide occurrence

There was a general increase in recorded landslide occurrence between 2004 to March 2010, followed by a general decrease in landslide occurrence through to April 2015, after which landslide incidence has generally increased (Fig. 6a). Petley (2012) identified improvements in the reporting of single fatality landslides as contributing to the general increase in events in the fatal landslide record from 2004 to 2010. The number of fatalities resulting from non-seismic landslide events between 2004 and 2016 was 55997. Fig. 6b, shows that the pentad series of fatality is very noisy; the data do not contain an increasing or decreasing trend, nor are there distinguishable medium-term peaks in the data. Very few landslide events generated more than 1000 fatalities (0.1%), and only one landslide resulted in more than 5000 fatalities. This was the Kedarnath landslide in June 2013 in Uttarakhand state, India, which was caused by extreme meteorological conditions that generated flooding and two large landslides in a mountainous area occupied by thousands of religious pilgrims (Allen *et al.*, 2016).

Landslide events by the number of fatalities are grouped by the infinite series (1, 2, 4, 8, 16…). There is a significant increasing trend in single-fatality landslides (Fig. 6c); 29% of landslides were single-fatality events. There is also a weaker decreasing trend in landslide events resulting in 64 to 128 fatalities (Fig. 6d); 1% of landslide events were in this group. No other grouping contained a significant trend with time. Both the single fatality and 64 to 128 fatality series are above the regression line in 2010 (Fig. 6c and 6d). Removing these two groups from the global series (Fig. 6e) it is evident that single fatality events enhanced the peak around 2010, and in 2016.

By year, different geographical regions experience above/below average landslide activity (multi-fatality landslide events, Fig. 6f; single-fatality landslides, Fig. 6g). In 2005, 2009, 2010 and 2011, several regions experienced greater than average landslide occurrence simultaneously. The high impact of landslides globally in 2010, has been discussed by previous authors (Kirschbaum *et al.*, 2012; 2015; Petley, 2012; Sepúlveda and Petley, 2015). The peak in landslide activity was generated by anomalous landslide occurrence in several regions simultaneously (Fig. 6f and 67g), but overall the geographical pattern of rainfall triggered landslide events in 2009 and 2010 reflects the occurrence of a moderate El Niño in 2009 and a moderate La Niña in 2010 (NOAA, 2018b).

In Central America, Kirschbaum *et al*. (2012) showed that rainfall was significantly above average in the summer months in 2010, particularly in September. This increase was linked to the known impacts of La Niña events on tropical cyclone frequency and track (*e.g.* Elsner *et al.*, 1999; Curtis *et al.*, 2007). By number, 2010 was the year in which the most landslides (17 events, compared with an average 6 events per year), were directly associated with tropical cyclones in reports or related to storm tracks (based on NOAA, 2018c). Although, these landslide events only equate to 35% of all rainfall-triggered landslide events within 2010, the remaining 65% of events, not triggered by a tropical cyclone all occurred during the hurricane season (May to November), likely due to unsettled weather associated with warm sea surface temperatures in the region. Central America receives tropical cyclones from the Atlantic basin and the North Pacific basin (NOAA, 2018c). Storms from the Atlantic basin may make landfall along the eastern coastline of Central America and travel inland, occasionally retaining enough energy to cross over into the Pacific. Storms that have crossed over basins or new storms, which have formed in the Northeast Pacific basin, may make landfall on the western coast of Central America. Not only were the frequency of landfalling tropical storms and hurricanes elevated from both basins in 2010, but the track of these storms intercepted populated areas in steep terrain (NOAA, 2018c). The majority of rainfall-triggered landslide events in Central America in 2010 were in Mexico and Guatemala (43% and 37%, respectively). In Guatemala, eight landslide events were triggered by Tropical Storm Agatha in late May 2010, causing 182 fatalities. Four landslide events were associated with Hurricane Alex which travelled up the east coast of Guatemala, Honduras and then inland to Mexico in late June-July 2010. Hurricane Karl then made landfall on the east coast of Mexico in September: two landslide events are associated with this storm (killing 12), but a succession of fatal landslides in the states of Oaxaca, Chiapis and Puebla through which the hurricane passed, were noted in the weeks following the storm.

Sepúlveda and Petley (2015) observed a weak correlation between La Niña conditions in late 2010-2011 and heightened landslide activity in Colombia and Venezuela. Considering a longer time series (2004 to 2016), this study identifies above average landslide activity in several nations in South America in 2009 and 2011. In Brazil, 54% of all rainfall-triggered events occurred between 2009 and

2011. Activity peaked in December 2009 to April 2010 (El Niño) and January 2011 (La Niña), corresponding with the seasonal El Niño-Southern Oscillation (ENSO) rainfall patterns observed by Grimm and Tedeschi (2009). The number of landslide events in Venezuela and Colombia between 2009 and 2011 peaked in November 2010, associated with positive rainfall anomalies during the austral summer La Niña (Tedeschi *et al.*, 2013).

The majority of landslide events in East Asia occur in China (83%); in 2010, 87% of all rainfall-triggered events were located in China, and rainfall-triggered landslide occurrence (67 landslide events) was above the mean (45 landslide events). From a shorter period of observation, Kirschbaum *et al.* (2012) identified a high incidence of rainfall-triggered landslides (fatal and non-fatal) in central eastern China in 2010: particularly in July and August corresponding with a peak in rainfall. Rainfall-triggered landslides were above average for most months in 2010 in China, but May through to September was very active (57 landslide events compared with an average 38). The East Asian subtropical summer monsoon (a component of the East Asian monsoon) has a significant effect on seasonal variations in rainfall across China (He and Liu, 2016), and rainfall patterns alter in response to ENSO conditions (Yang and Lau, 2004; He et al., 2007; Zhou *et al.*, 2014).

In China in 2010, there were fewer than average landslide events triggered by tropical cyclones from the Northwest Pacific basin. There was low typhoon activity due to the rapid transition from the 2009/2010 El Niño to the 2010/2011 La Niña, which altered airflows in the North West Pacific basin (Kim *et al.*, 2012). Conversely, in the Philippine domain, tropical cyclone occurrence was above average in July to December 2009 (Corporal-Lodangco *et al.*, 2015). During the northern hemisphere summer months of an El Niño, the genesis location of tropical cyclones shifts eastwards (Chan 1985; 2000; Chia and Ropelewski, 2002). In these conditions, cyclones travel further before they may make landfall, enabling them to strengthen (Camargo and Sobel, 2005), and there is a tendency for more storms to affect the northern-central Philippines (Lyon and Camargo, 2009). In 2009, 67% of rainfall-triggered landslide events in the Philippines were associated with tropical cyclones: 60 landslide events compared with an average 12 triggered by tropical cyclones. As noted previously, many of these were triggered on the same day (8 October 2009) by Typhoon Parma.

Although the peak in landslides in South East Asia in 2009 is dominated by typhoon triggered landslides in the Philippines, there was an increase in landslides in Indonesia (33 landslide events compared with an average of 24 per year); of these 24 events were triggered by rainfall, 8 by mining and one trigger was not known. Rainfall-triggered landslide events were very slightly above average in Indonesia in 2009 but it was the events triggered by human activity that contributed most to the anomalous landsliding in Indonesia. These landslides are discussed in the next section.

Between 2004 and 2016, four El Niño events occurred: weak El Niño (2004/2005, 2006/2007), strong El Niño (2009/2010) and very strong El Niño (2014/2016; NOAA, 2018b). Weak La Niña was observed in 2005/2006, 2008/2009, 2016, and strong La Niña in 2007/2008 and 2010/2011 (NOAA, 2018b). There does not appear to be a consistent relationship between ENSO phase and the regional distribution of landslides, although elevated regional rainfall (and thus landslides) has been associated with ENSO sea-surface temperature (SSTs) anomalies. The peak in landslide events in Central America in 2005 is composed predominantly of tropical storm and hurricane triggered landslides in El Salvador, Mexico, Guatemala and Honduras. The 2005 North Atlantic Hurricane season was the most active since records began in 1851, driven by high SSTs in the Tropical North Atlantic (10°-20°N) linked with global warming and the 2004/2005 El Niño (Trenberth and Shea, 2005). Landslide events were also above average in 2005 in East Asia: most events occurring in China, triggered by monsoon rainfall. In South Asia, landslide events peaked in 2007, 2014 and 2016, the majority associated with monsoon rainfall in Bangladesh, India, Nepal and Pakistan. Variability in rainfall from the South Asian monsoon is related to the interaction between SSTs in the Indian Ocean dipole (IOD) and ENSO (*e.g.* Ashok *et al.*, 2007; Lu *et al.*, 2017).

The complexity of climate systems means it is not possible to draw conclusions on the relationship between climate mode and landslide occurrence from this 13 year global dataset. However, longer local records show promise at unpicking the impact of climate cycles on landslides.

3.3. NSNR landslide Triggers

Of the 4862 non-seismic landslide events in the complete database, 770 (16%) were generated by a NSNR trigger, and resulted in a total 3725 fatalities (Fig. 7). The majority of landslides were triggered by mining (232 multi-fatality landslide events, 67 single-fatality landslides), construction (170 multi-fatality landslide events, 140 single-fatality landslides) or illegal hillcutting (60 multi-fatality landslide events, 27 single-fatality landslides); and the majority of fatalities in all cases were people at work (90%, 76% and 84% respectively). Globally there is a statistically significant increase in events by these three triggers (Fig. 8a, 8b and 8c); multi-fatality landslide events are differentiated from single-fatality landslides, which increased with time independent of trigger (Fig. 6c). By country, most construction triggered landslide events occurred in India (28%), followed by China (9%), Pakistan (6%), the Philippines (5%), Nepal (5%) and Malaysia (5%; Fig. 9a). On average construction triggered landslide events killed three people, however a particularly severe landslide in Shenzhen, China in December 2015 killed 77 people. The event involved the collapse of construction waste on worker quarters in an industrial site. Interestingly, the context in which the landslides occur differs between countries. In China, the majority of events (52%) occur in urban construction sites, while very few landslides occur on roads (7%). Conversely, in India and Nepal, 30% and 43% of landslide events triggered by construction occurred on roads.

Transportation is a “crucial driver of development” (World Bank, 2018b); however, in mountain regions roads are closely connected with landslide risk (Lennartz, 2013). The road network in Nepal has quadrupled in length over the last 18 years (Govt. of Nepal, 2016), and in India it has nearly tripled in length in 24 years (Govt. of India, 2016). Population growth is frequently accompanied by the expansion of infrastructure and settlements (Gardner and Dekens, 2007), and this is true in India and Nepal, which have grown by ~7% between 2010 and 2015 (World Bank, 2018a). Both countries are on a trajectory to expand their national road networks further. Increased landslide activity in the Himalayan region has been associated with road construction (Ives and Messerli, 1989; Haigh *et al.*, 1989; Valdiya, 1998; Barnard *et al.*, 2001; Petley *et al.*, 2007; Sait *et al.*, 2011; Singh *et al.*, 2014). Hearn and Shakya (2017) highlighted that road construction without proper route choice, engineering design and management of spoil, increases landslide susceptibility. Fatal landslides triggered by road construction indicate that excavation may not always be undertaken with due care and appropriate slope engineering. Furthermore, the coincidence of construction worker and road user fatalities from the same landslide suggests that there is pressure to keep roads under construction open. Ives and Messerli (1989) emphasised the economic impact when roads are closed.

Between 2004 and 2016, China experienced a 6% growth in population to 1.379 billion, and a 16% rise in the proportion of the population living in urban areas (World Bank, 2018a). Urban growth in China is driven by political policy for economic growth; economic reforms from 1978, opened China's markets to foreign investors and relaxed migration controls, prompting rapid rural-urban migration (Ma, 2002; Anderson and Ge, 2004). Although urbanization is encouraged by China to increase domestic consumption, urban growth is often uncontrolled (Fang and Pal, 2016), leading to rapid land conversion, dispersion and fragmentation of development (Schneider and Woodcock, 2008). Critically, many of China's largest cities are bounded by mountains, and urban sprawl is encroaching on land unsuitable for development (Yu and Li, 2011). Reports in the database indicate that fatal landslides in urban construction sites in China often occurred when engineered cut slopes failed above the construction site (*e.g.* Zhang *et al.*, 2012), from improper construction of foundations leading to building collapse before completion (*e.g.* Srivastava *et al*., 2012), or from mismanagement of construction and demolition waste (*e.g.* Yang *et al.*, 2017). In these entirely preventable circumstances, explicit national regulation and enforcement should reduce construction related landslide impact in China.

The increase in events triggered by mining is driven by the increase in landslides triggered by illegal or unregulated extraction (Fig. 8d); landslides triggered by legal mining (Fig. 8e) or where the legitimacy of the mining is unknown (Fig. 8f), do not show a statistically significant trend. By country, India (12%), Indonesia (11.7%), China (10%), Pakistan (7%) and Philippines (7%) contribute most to the record of landslides triggered by mining (Fig. 9b). Fatal landslides triggered by illegal mining practises have occurred in 32 countries (Fig. 9c). By number of events, Indonesia (24) and India (15) rank the highest, however by number of fatalities Myanmar (403 fatalities from 9 landslide events) stands out. Shifts in spending power and the infusion of the internet and smart-technology in daily life have driven an exponential increase in the consumption of electronics, placing pressure on the demand for rare earth elements (Dutta *et al.*, 2016). Furthermore, growth in the precious stone market fuelled both by economic uncertainty, and a growing middle class in Asian nations such as China, where gemstones are a key part of cultural heritage (The Economist, 2011), is thought to have led to an increase in the number of small-scale mining operations globally (Hruschka and Echavarría, 2011), and the upscaling of small-scale mines to larger scale operations. Fatal landslides in Myanmar (Burma) have significantly increased because of the unregulated expansion in jade mining within the Kachin state. Critically, the high value of jade and lack of enforced operator accountability appears to be driving poor mining practises, which place workers and local residents at risk of slope collapse (Global Witness, 2015). Demand for rare earth elements and gemstones are thus driving an increase in mining-related landslides, with the potential for landslide occurrence to rival that associated with rural road expansion.

Cutting slopes for the purposes of obtaining earth surface materials, or to alter slope geometry during construction, may result in slope failure if the site is not properly engineered. The term hill-cutting is used here in relation to discrete slopes that have been altered without permission for the purposes of small-scale construction, earth material extraction or agriculture. Hill-cutting is most strongly associated with urban areas in Bangladesh in the academic literature (*e.g*. Chittagong; Ahmed, 2015 or Syhlet; Islam *et al.*, 2006). In the fatal landslide database it is an increasing problem in Bangladesh, India and Nepal (Fig. 8c and 9d). Most fatalities occurred as people collected hillslope materials for construction of their housing in rural communities, and reports indicate those involved were from poor families living in informal settlements. In total, 11 of the 87 landslide events were directly related to the practice of using hillslope coloured clay for the decorative coating of houses for a religious festival; of these, nine occurred in Nepal. Critically, children are often caught up in slides triggered by hill-cutting in Nepal: at least 40% of landslide victims were children, while a further 25% of victims were a combination of adults (predominantly women) and children working together. Conversely, in Bangladesh the majority of victims were adults (78%) of which 79% were male. In Nepal, India and Bangladesh, clay is an important local building material for housing, particularly in settlements not connected to the road network, but there is a legal framework in Bangladesh to prevent hill-cutting (Building Construction Act 1952, 1990 and the Bangladesh Environmental Conservation Act 1995; Murshed, 2013). Building codes in Nepal provide basic guidance on slope stability, specifically slope excavation, identification of slope instability and construction of foundations (DUDBC, 1994); however residents in rural communities may not have access to this information and be unaware of the hazard (Oven *et al.*, 2008). Furthermore, in India it was noted that building regulations do not account for the geo-environmental context of the settlement, sometimes lack clarity, and are difficult to uphold due to a shortage of technical experts and inadequate provision to stop illegal activity (Kumar and Pushplata, 2014).

While this section discusses fatal landslides triggered by human activity, many rainfall-triggered landslides occur on slopes which have been modified during construction (82 landslide events), agriculture and forestry (45 landslide events) and mining (123 landslide events); or at sites where storage of waste has not been poorly managed (16 landslide events). Of course, it is expected the majority of fatal landslides (94%) will occur within settlement boundaries or along infrastructure, however it is evident from this database of events that human action damages slopes increasing their susceptibility to fail.

4. Discussion and Conclusion

With the benefit of a 13 year time series, this study builds on past analyses of the GLFD, providing not only an update on the spatial and temporal distributions of landslide impact, but also serving to highlight the importance of annual climate variability in specific landslide prone regions on the global record. In addition, it provides new insights into the impact of human activity on landslide incidence. The data does not indicate a discernible long-term increase or decrease in global landslide impact; rather the record shows that there is considerable inter-annual variability in global landslide event incidence. The more active years have been associated with recognised regional patterns of rainfall, in part driven by global climate anomalies, but there is no simple relationship with, for example, ENSO. Relating climate modes to patterns of landsliding is challenging because of climate complexity and change, requiring 30 year + datasets. Increased understanding of the impact of ENSO diversity on regional climate, will improve models forecasting seasonal rainfall distribution and landslide impact. This is particularly important in acutely affected areas such as India, China and Nepal.

Human disturbance (land use change) may be more detrimental to future landslide incidence than climate change (Crozier, 2010; Anderson and Holcombe, 2013), and this is evidenced by a number of studies (Innes, 1983; Glade, 2003; Soldati *et al.*, 2004; Imaizumi *et al*., 2008; Borgatti and Soldati, 2010; Lonigro *et al.*, 2015). A comprehensive review of climate-landslide studies by Gariano and Guzzetti (2016) found the majority of papers (80%) showed a causal relationship between climate change and landslides. However, the authors highlight the significant uncertainties surrounding our current understanding of climate-landslide interaction. Specifically, the limited geographic scope of research, challenges in downscaling climate scenarios to slope stability models, and complex interactions between natural and human induced drivers of landslide activity. Gariano and Guzzetti (2016) demonstrate that different climate variables will effect different landslide types and slope settings. There is a high confidence that glacial retreat and permafrost degradation will increase slope instabilities in high mountain areas in the long term, and high confidence that changes in heavy precipitation will affect some regions. However, there is low confidence in projections for shallow landslide activity in temperate and tropical regions, because of the coincident effects of human land use practise (Seneviratne *et al.*, 2012). Further research is required to evaluate the impact of climate change and human disturbance in different localities.

Our analyses have demonstrated that fatal landslide occurrence triggered by human activity is increasing, driven by construction, illegal mining and illegal hillcutting. Fatal landslides occur when construction and mining: (1) do not apply appropriate slope engineering, (2) mismanage spoil and, (3) do not undertake a feasibility assessment (Hearn and Shakya, 2017). Appropriate building regulations that account for the geo-environmental context of the settlement, provide clear guidance on engineering and are enforced by local technical experts, are paramount in managing landslide risk associated with urbanization and natural resource exploitation.

Holcombe et al. (2016) emphasised that planning policy alone is not sufficient to control landslide risk in developing nations. This is due to the rapid and informal nature of construction, and low-income of residents, who cannot finance expert guidance when building their homes. Settlements are often built on hazardous land around urban centres and on roadsides, because of the benefits of service access and employment opportunities (Smyth and Royale, 2000; Oven *et al.*, 2008; Lennartz, 2013; Anhorn *et al.*, 2015). Hillcutting is the dominant driver of instability during informal construction (Holcombe *et al.*, 2016), and our results indicate fatal landslide events triggered by hillcutting are increasing in Bangladesh, India and Nepal. Several landslides were triggered when people cut slopes to collect coloured clay to decorate their houses for religious festivals. Here, communication of landslide risk by local non-governmental organisations (NGOs) could prevent future fatalities from this practice. Where governments are limited in capacity at a local level, NGOs are important in implementing disaster risk reduction (Jones *et al.*, 2016), such as supporting community-based slope engineering (*e.g.* Mossaic; Anderson and Holcombe, 2006).

Reporting of fatal landslides is likely to increase with the global growth in mobile technology and internet access, particularly in remote mountain regions. Furthermore, advances in web mining (data retrieval from the internet based on search criteria) and text mining (transforms unstructured data into structured to discover knowledge) using machine learning offer methods to improve capture of landslide reporting and data evaluation (*e.g.* Bhatia and Khalid, 2008; Kumar et al., 2018). Global landslide databases are designed to capture general trends in landslide occurrence rather than provide data for local quantitative risk assessment. Continued collection of the database will develop our understanding of the effect of climate and human disturbance on global landslide impact. The dataset is a useful tool in identifying acutely landslide prone parts of the world and specific local drivers of landslide impact; thereby highlighting locations which would benefit from further development in early warning technology, landslide risk assessment and community capacity building. This is in support of the future directions of the International Consortium on Landslides (Alcantara-Ayala et al., 2017).

Figures

Figure 1. (**a**) The location of non-seismically triggered fatal landslide events from 2004 to 2016. Individual landslide events shown by a black dot. (**b**) Number of non-seismically triggered fatal landslide events from 2004 to 2016 by country. (**c**) The Gross National Income per capita (US $) by country (World Bank, 2018), and the location of major urban centres globally (ESRI, 2018).

Figure 2. The occurrence of non-seismically triggered landslide events from 2004 to 2016, and cumulative total of recorded events. The data are arranged by pentads (five-day bins), starting on the 1st January each year, thus the first pentad includes records for 1-5 January, and there are a total 73 pentads. A simple 25-day moving average is shown.

Figure 3. (**a**) The occurrence of rainfall triggered landslide events from 2004 to 2016 (blue). The data are arranged by pentads (five-day bins), starting on the 1st January each year. A simple 25-day moving average is shown. The 25-day moving average for all non-seismically triggered landslide events, is shown in black. (**b**) The occurrence of NSNR landslide events from 2004 to 2016 (purple). The data are arranged by pentads (five-day bins), starting on the 1st January each year. A simple 25-day moving average is shown. The 25-day moving average for all non-seismically triggered landslide events, is shown in black.

Figure 4. Mean number of landslides per pentad through the annual cycle for all rainfall-triggered landslides, and by geographical region. The 20th pentad is the 6-10 April, the 40th pentad is 15-19 July and 60th pentad is 23- 27 October.

Figure 5. Mean daily rainfall (mm) by month between 2004 and 2016 summarised by geographical sub-region (blue bars). Global Precipitation Climatology Centre data (Xie *et al.*, 2013; GPCC, 2018) was processed in ESRI ArcMap and Matlab. Mean daily rainfall-triggered landslide event occurrence by month between 2004 and 2016 (black line). Daily values are used to overcome the difference in month length.

Figure 6. (**a**) The occurrence of non-seismically triggered landslide events from 2004 to 2016: 25 day and 1 year moving average (see also Fig. 2). (**b**) The number of fatalities from non-seismically

triggered landslide events from 2004 to 2016 by pentad with 25 day moving average. (**c**) Number of single fatality landslides 2004 to 2016. (**d**) Number of landslide events incurring 64 to 128 fatalities per event from 2004 to 2016. (**e**) Comparison of the complete landslide series (Fig. 6a) and multi-fatality landslide series (excluding the 64 to 128 fatality class). (**f**) Anomalies in landslide event occurrence by year by geographical region (multi-fatality events). (**g**) Anomalies in landslide occurrence by year, by geographical region (single fatality events). Values greater than 1 standard deviation from the mean are shown by a grey circle. Values greater than 2 standard deviations from the mean are shown by a black circle.

Figure 7. Distribution of triggers of NSNR landslide events (770 events).

Figure 8. Number of landslide events triggered per year by (**a**) construction, (**b**) mining, (**c**) illegal hill-cutting, (**d**) illegal mining, (**e**) legal mining and (**f**) mining (not specified). The black series contains only multi-fatality landslide events. The grey series contains single and multi-fatality landslide events.

Figure 9. By country, the number of landslide events triggered by (**a**) construction, (**b**) mining, (**c**) illegal mining and (**d**) illegal hill-cutting, between 2004 to 2016.

Data availability

The GFLDe (2004 to 2016) is not currently available to the public, however a web-platform is under-development to host the data openly at the University of Sheffield, UK. Due for release in 2018.

Appendix A

Figure A1. Sample autocorrelation plot for the pentad rainfall-triggered landslides. The 99% confidence interval is shown by the blue horizontal lines.

Figure A2. Sample autocorrelation plot for the pentad NSNR landslides. The 99% confidence interval is shown by the blue horizontal lines.

Appendix B

Table B1. Hierarchal linear regression results comparing the impact of seasonality in geographical regions with the global mean number of landslides per pentad through the annual cycle (see Fig. 4). The data series for each geographical region are sequentially added into the regression (such that the second row of the table is a regression of S.Asia + S.E. Asia with the global series).

Author contribution

DP developed the methodology (2002-2003) and has consistently collected the database since 2004. MF analysed the data and wrote up the results for this submission. DP contributed to writing.

Competing interests

The authors declare that they have no conflict of interest.

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References

Ahmed, B.: Landslide susceptibility mapping using multi-criteria evaluation techniques in Chittagong Metropolitan Area, Bangladesh, Landslides, 12(6), 1077–1095, doi:10.1007/s10346-014-0521-x, 2015.

Alcántara-Ayala, I., Sassa, K., Mikoš, M., Han, Q., Rhyner, J., Takara, K., Nishikawa, S., Rouhban, B. and Briceño, S.: The 4th World Landslide Forum: Landslide Research and Risk Reduction for Advancing the Culture of Living with Natural Hazards, Int J Disaster Risk Sci, 8(4), 498–502, doi:10.1007/s13753-017-0139-4, 2017.

Alexander, D.: Urban landslides, Progress in Physical Geography: Earth and Environment, 13(2), 157–189, doi:10.1177/030913338901300201, 1989.

Allen, S. K., Rastner, P., Arora, M., Huggel, C. and Stoffel, M.: Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition, Landslides, 13(6), 1479–1491, doi:10.1007/s10346-015-0584-3, 2016.

Anderson, M. G. and Holcombe, E.: Community-Based Landslide Risk Reduction: Managing Disasters in Small Steps, World Bank Publications., 2013.

Anderson, M. G. and Holcombe, E.A., Sustainable Landslide Risk Reduction in Poorer Countries, Proceedings of the Institution of Civil Engineers- Engineering Sustainability, 159, 23-30, 2006.

Anderson, G. and Ge, Y.: Do Economic Reforms Accelerate Urban Growth? The Case of China, Urban Stud., 41(11), 2197–2210, doi:10.1080/0042098042000268410, 2004.

Anderson, M. B.: Metropolitan areas and disaster vulnerability: a consideration for developing countries, [online] Available from: https://www.popline.org/node/325322, 1992.

Anhorn, J., Lennartz, T., and Nüsser, M., Rapid urban growth and earthquake risk in Musikot, mid-western hills, Nepal, Erdkunde, 69(4), 307-325, 2015.

Ashok, K. and Saji, N. H.: On the impacts of ENSO and Indian Ocean dipole events on sub-regional Indian summer monsoon rainfall, Nat. Hazards, 42(2), 273–285, doi:10.1007/s11069-006-9091-0, 2007.

Barnard, P. L., Owen, L. A., Sharma, M. C. and Finkel, R. C.: Natural and human-induced landsliding in the Garhwal Himalaya of northern India, Geomorphology , 40(1), 21–35, doi:10.1016/S0169-555X(01)00035-6, 2001.

Bennett, G. L., Miller, S. R., Roering, J. J. and Schmidt, D. A.: Landslides, threshold slopes, and the survival of relict terrain in the wake of the Mendocino Triple Junction, Geology, 44(5), 363–366, doi:10.1130/G37530.1, 2016.

Bhatia, M. and Khalid, A. K.: Information retrieval and machine learning: Supporting technologies for web mining research and practice, Webology, 5(2), [online] Available from: http://www.webology.org/2008/v5n2/a55.html, last access: 15 February 2018, 2008.

Borgatti, L. and Soldati, M.: Landslides as a geomorphological proxy for climate change: A record from the Dolomites (northern Italy), Geomorphology , 120(1), 56–64, doi:10.1016/j.geomorph.2009.09.015, 2010.

Camargo, S. J. and Sobel, A. H.: Western North Pacific Tropical Cyclone Intensity and ENSO, J. Clim., 18(15), 2996–3006, doi:10.1175/JCLI3457.1, 2005.

Carrara, A., Crosta, G. and Frattini, P.: Geomorphological and historical data in assessing landslide hazard, Earth Surf. Processes Landforms, 28(10), 1125–1142, doi:10.1002/esp.545, 2003.

Chan, J. C. L.: Tropical Cyclone Activity over the Western North Pacific Associated with El Niño and La Niña Events, J. Clim., 13(16), 2960–2972, doi:10.1175/1520-0442(2000)013<2960:TCAOTW>2.0.CO;2, 2000.

Chan, J. C. L.: Tropical Cyclone Activity in the Northwest Pacific in Relation to the El Niño/Southern Oscillation Phenomenon, Mon. Weather Rev., 113(4), 599–606, doi:10.1175/1520-0493(1985)113<0599:TCAITN>2.0.CO;2, 1985.

Chia, H. H. and Ropelewski, C. F.: The Interannual Variability in the Genesis Location of Tropical Cyclones in the Northwest Pacific, J. Clim., 15(20), 2934–2944, doi:10.1175/1520-0442(2002)015<2934:TIVITG>2.0.CO;2, 2002.

Crozier, M. J.: Deciphering the effect of climate change on landslide activity: A review, Geomorphology , 124(3), 260–267, doi:10.1016/j.geomorph.2010.04.009, 2010.

Curtis, S., Salahuddin, A., Adler, R. F., Huffman, G. J., Gu, G. and Hong, Y.: Precipitation Extremes Estimated by GPCP and TRMM: ENSO Relationships, J. Hydrometeorol., 8(4), 678–689, doi:10.1175/JHM601.1, 2007.

DUDBC, Building Codes, Department of Urban Development and Building Construction, Ministry of Urban Development, Government of Nepal, Nepal: http://www.dudbc.gov.np/?lang=en, last access: 20 February 2018, 1994.

Dutta, T., Kim, K.-H., Uchimiya, M., Kwon, E. E., Jeon, B.-H., Deep, A. and Yun, S.-T.: Global demand for rare earth resources and strategies for green mining, Environ. Res., 150, 182–190, doi:10.1016/j.envres.2016.05.052, 2016.

Elsner, J. B., Kara, A. B. and Owens, M. A.: Fluctuations in North Atlantic Hurricane Frequency, J. Clim., 12(2), 427–437, doi:10.1175/1520-0442(1999)012<0427:FINAHF>2.0.CO;2, 1999.

Espinoza Villar, J. C., Ronchail, J., Guyot, J. L., Cochonneau, G., Naziano, F., Lavado, W., De Oliveira, E., Pombosa, R. and Vauchel, P.: Spatio-temporal rainfall variability in the Amazon basin countries (Brazil, Peru, Bolivia, Colombia, and Ecuador), Int. J. Climatol., 29(11), 1574–1594, doi:10.1002/joc.1791, 2009.

ESRI (2018) World Cities data, http://www.arcgis.com/home/item.html?id=dfab3b294ab24961899b2a98e9e8cd3d, last access: 19/02/2018

Fang, Y. and Pal, A., Drivers of Urban Sprawl in Urbanizing China – A Political Ecology Analysis, Environment and Urbanization, 28(2), 599-616, DOI: 10.1177/0956247816647344, 2016.

GADM, GADM maps and data, https://gadm.org/index.html, last accessed: 1 June 2017, 2017.

Garcia, N. Ferreira, R.N. and Latrubesse, E.M.: Ch1 Climate and Geomorphologic-related Disasters in Latin America, in: Latrubesse, E.M. (eds.) Natural Hazards and Human-Exacerbated Disasters in Latin America: Special Volumes of Geomorphology, Elsevier, Nature, Amsterdam, Netherlands, 550 pp., 2009

Gardner, J. S. and Dekens, J.: Mountain hazards and the resilience of social–ecological systems: lessons learned in India and Canada, Nat. Hazards, 41(2), 317–336, doi:10.1007/s11069-006-9038-5, 2007.

Glade, T., and Crozier, M.J.: The Nature of Landslide Hazard Impact, in: Landslide Hazard and Risk, John Wiley & Sons Ltd, Chichester, England, 41–74, 2005.

Glade, T.: Landslide occurrence as a response to land use change: a review of evidence from New Zealand, Catena, 51(3), 297–314, doi:10.1016/S0341-8162(02)00170-4, 2003.

Global Witness, Jade: Myanmar's "big state secret", Global Witness Report, October 2015: www.globalwitness.org, last access: 15 December 2016, 2015.

Google Earth, https://earth.google.com/web/, last access: 8 June 2018, 2018.

Google Maps, https://www.google.co.uk/maps, last access: 8 June 2018, 2018.

Govt. of India, Basic Road Statistics of India 2015-2016, Ministry of Road Transport and Highways, Transport Research Wing, Government of India, New Delhi, India, 2016.

Govt. of Nepal, Statistics of strategic road network SSRN 2015/2016, Department of Roads, Ministry of Physical Infrastructure and Transport, Government of Nepal, Nepal, 2016.

GPCC, Global Precipitation Climatology Centre monthly precipitation dataset, file: precip.mon.combined.total.v7.nc, https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html, last access: 10 February 2018, 2018.

Grimm, A. M. and Tedeschi, R. G.: ENSO and Extreme Rainfall Events in South America, J. Clim., 22(7), 1589–1609, doi:10.1175/2008JCLI2429.1, 2009.

Guha-Sapir, D., Below, R. and Hoyois, P. H.: EM-DAT: International Disaster Database, http://www.emdat.be, Université Catholique de Louvain, Brussels, Belgium, last access 19 February 2018.

Haigh, M. J., Rawat, J. S. and Bartarya, S. K.: Environmental Indicators of Landslide Activity along the Kilbury Road, Nainital, Kumaun Lesser Himalaya, Mt. Res. Dev., 9(1), 25–33, doi:10.2307/3673462, 1989.

Hallegatte, S., Vogt-Schilb, A., Rozenberg, J., and Bangalore, M.: Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters. World Bank Publications, Washington, USA, 201 pp., 2016.

He, J. and Liu, B.: The East Asian subtropical summer monsoon: Recent progress, J. Meteorol. Res., 30(2), 135–155, doi:10.1007/s13351-016-5222-z, 2016.

He, J., Ju, J., Wen, Z., Junmei, L. and Jin, Q.: A review of recent advances in research on Asian monsoon in China, Adv. Atmos. Sci., 24(6), 972–992, doi:10.1007/s00376-007-0972-2, 2007.

Hearn, G. J. and Shakya, N. M.: Engineering challenges for sustainable road access in the Himalayas, doi:10.1144/qjegh2016-109, 2017.

Hearn, G. J. (ed.): Slope Engineering for Mountain Roads. Geological Society, London, Engineering Geology Special Publications, 24, 2011.

Hervás, J., and Bobrowsky, P.: Mapping: Inventories, susceptibility, hazard and risk, in: Sassa,K. and Canuti, P. (Eds.), Landslides – Disaster Risk Reduction, Springer, Berlin, Germany, 321–349, 2009.

Holcombe, E. A., Beesley, M. E. W., Vardanega, P. J. and Sorbie, R.: Urbanisation and landslides: hazard drivers and better practices, Proc. Inst. Civ. Eng. - Geotech. Eng., 169(3), 137–144, doi:10.1680/jcien.15.00044, 2016.

Hong, Y., Adler, R. and Huffman, G.: Use of satellite remote sensing data in the mapping of global landslide susceptibility, Nat. Hazards, 43(2), 245–256, doi:10.1007/s11069-006-9104-z, 2007.

Hruschka, F. and Echavarría, C., Rock-Solid Chances for Responsible Artisanal Mining, Series on Responsible ASM No.3, Alliance for Responsible Mining, 2011.

Hungr, O., Leroueil, S. and Picarelli, L.: The Varnes classification of landslide types, an update, Landslides, 11(2), 167–194, doi:10.1007/s10346-013-0436-y, 2014.

Imaizumi, F., Sidle, R. C. and Kamei, R.: Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan, Earth Surf. Processes Landforms, 33(6), 827–840, doi:10.1002/esp.1574, 2008.

Innes, J. L.: Lichenometric dating of debris-flow deposits in the Scottish Highlands, Earth Surf. Processes Landforms, 8(6), 579–588, doi:10.1002/esp.3290080609, 1983.

Islam, M. S., Jahid Hasan, G. M. and Chowdhury, M. A. I.: Destroying hills in the northeastern part of Bangladesh: A qualitative assessment of extent of the problem and its probable impact, Int. J. Environ. Sci. Technol., 2(4), 301–308, doi:10.1007/BF03325890, 2006.

Ives, J.D. and Messerli, B., The Himalayan Dilemma: Reconciling Development and Conservation, The United Nations University, Routledge, London, 1989.

Jones, S., Oven, K. J. and Wisner, B.: A comparison of the governance landscape of earthquake risk reduction in Nepal and the Indian State of Bihar, International Journal of Disaster Risk Reduction, 15, 29–42, doi:10.1016/j.ijdrr.2015.10.011, 2016.

Kim, J.-H., Ho, C.-H., Kim, H.-S. and Choi, W.: 2010 Western North Pacific Typhoon Season: Seasonal Overview and Forecast Using a Track-Pattern-Based Model, Weather Forecast., 27(3), 730–743, doi:10.1175/WAF-D-11-00109.1, 2012.

Kirschbaum, D., Stanley, T. and Zhou, Y.: Spatial and temporal analysis of a global landslide catalog, Geomorphology , 249, 4–15, doi:10.1016/j.geomorph.2015.03.016, 2015.

Kirschbaum, D., Adler, R., Adler, D., Peters-Lidard, C. and Huffman, G.: Global Distribution of Extreme Precipitation and High-Impact Landslides in 2010 Relative to Previous Years, J. Hydrometeorol., 13(5), 1536–1551, doi:10.1175/JHM-D-12-02.1, 2012.

Kirschbaum, D. B., Adler, R., Hong, Y., Hill, S. and Lerner-Lam, A.: A global landslide catalog for hazard applications: method, results, and limitations, Nat. Hazards, 52(3), 561–575, doi:10.1007/s11069-009-9401-4, 2010.

Kubota, H., Shirooka, R., Matsumoto, J., Cayanan, E. O. and Hilario, F. D.: Tropical cyclone influence on the long-term variability of Philippine summer monsoon onset, Prog Earth Planet Sci, 4(1), 27, doi:10.1186/s40645-017-0138-5, 2017.

Kumar, A. and Jaiswal, A.: Empirical Study of Twitter and Tumblr for Sentiment Analysis using Soft Computing Techniques, in Proceedings of the World Congress on Engineering and Computer Science, vol. 1, iaeng.org. [online] Available from: http://www.iaeng.org/publication/WCECS2017/WCECS2017_pp472-476.pdf, 2017.

Kumar, A. and Pushplata: Building regulations for hill towns of India, HBRC Journal, 11(2), 275–284, doi:10.1016/j.hbrcj.2014.06.006, 2015.

Lee, C.-F., Huang, W.-K., Chang, Y.-L., Chi, S.-Y. and Liao, W.-C.: Regional landslide susceptibility assessment using multi-stage remote sensing data along the coastal range highway in northeastern Taiwan, Geomorphology , 300, 113–127, doi:10.1016/j.geomorph.2017.10.019, 2018.

Lennartz, T.: Constructing Roads—Constructing Risks? Settlement Decisions in View of Landslide Risk and Economic Opportunities in Western Nepal, Mt. Res. Dev., 33(4), 364–371, doi:10.1659/MRD-JOURNAL-D-13-00048.1, 2013.

Lonigro, T., Gentile, F. and Polemio, M., The influence of climate variability and land use variations on the occurrence of landslide events (Subappennino Dauno, Southern Italy), Rend. Online Soc. Geol. Ital., 35, 192-195, doi: 10.3301/ROL.2015.98, 2015.

Lu, B., Ren, H.-L., Scaife, A. A., Wu, J., Dunstone, N., Smith, D., Wan, J., Eade, R., MacLachlan, C. and Gordon, M.: An extreme negative Indian Ocean Dipole event in 2016: dynamics and predictability, Clim. Dyn., 1–12, doi:10.1007/s00382-017-3908-2, 2017.

Lyon, B. and Camargo, S. J.: The seasonally-varying influence of ENSO on rainfall and tropical cyclone activity in the Philippines, Clim. Dyn., 32(1), 125–141, doi:10.1007/s00382-008-0380-z, 2009.

Ma, L. J. C.: Urban Transformation in China, 1949 – 2000: A Review and Research Agenda, Environ. Plan. A, 34(9), 1545–1569, doi:10.1068/a34192, 2002.

Magaña, V., Amador, J. A. and Medina, S.: The Midsummer Drought over Mexico and Central America, J. Clim., 12(6), 1577–1588, doi:10.1175/1520-0442(1999)012<1577:TMDOMA>2.0.CO;2, 1999

Moreiras, S. M.: Climatic effect of ENSO associated with landslide occurrence in the Central Andes, Mendoza Province, Argentina, Landslides, 2(1), 53–59, doi:10.1007/s10346-005-0046-4, 2005.

Murshed, M. M.: Cutting of hills and human tragedy: An example of law enforcement loophole in the southeastern region of Bangladesh, International Journal of Geomatics and Geosciences, 4(2), 410 [online] Available from: http://www.ipublishing.co.in/jggsarticles/volfour/EIJGGS4035.pdf, 2013.

Naylor, R. L., Battisti, D. S., Vimont, D. J., Falcon, W. P. and Burke, M. B.: Assessing risks of climate variability and climate change for Indonesian rice agriculture, Proc. Natl. Acad. Sci. U. S. A., 104(19), 7752–7757, doi:10.1073/pnas.0701825104, 2007.

NOAA, Tropical Cyclone Climatology, National Oceanic and Atmospheric Administration National Hurricane Center: https://www.nhc.noaa.gov/climo/, last access: 20 February 2018a.

NOAA, Cold and Warm episodes by season, Historical El Nino / La Nina episodes (1950-present), National Oceanic and Atmospheric Administration National Hurricane Center: http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php, last access: 20 February 2018b.

NOAA, Historical Hurricane Tracks: https://coast.noaa.gov/hurricanes/, last access: 20 February 2018c.

Open Street Map, https://www.openstreetmap.org/, last access: 8 June 2018, 2018

Oven, K.J., Petley, D.N., Rigg, J.R, Dunn, C.E. and Rosser, N.J., Landscape, livelihoods and risk: A study of community vulnerability to landslide events in Central Nepal, in: Aryal, K.R. and Gadema, Z. Climate change and disaster risk reduction, Disaster and Development Centre, School of Applied Science, Northumbria University, 94-102, 2008.

Planet Team (2017). Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA. https://api.planet.com.

Petley, D.: Global patterns of loss of life from landslides, Geology, 40(10), 927–930, doi:10.1130/G33217.1, 2012.

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(4), 487–496, doi:10.1144/1470-9236/09-001, 2010.

Petley, D. N.: On the impact of urban landslides, Geological Society, London, Engineering Geology Special Publications, 22(1), 83–99, doi:10.1144/EGSP22.6, 2009.

Petley, D. N., Hearn, G. J., Hart, A., Rosser, N. J., Dunning, S. A., Oven, K. and Mitchell, W. A.: Trends in landslide occurrence in Nepal, Nat. Hazards, 43(1), 23–44, doi:10.1007/s11069-006-9100-3, 2007.

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: Hungr, O., Fell, R., Couture, R. and Eberhardt, E. (Eds.) Landslide Risk Management, Taylor and Francis, London, UK, 367 – 373, 2005.

Rao, V. B. and Hada, K.: Characteristics of rainfall over Brazil: Annual variations and connections with the Southern Oscillation, Theor. Appl. Climatol., 42(2), 81–91, doi:10.1007/BF00868215, 1990.

Sati, S. P., Sundriyal, Y. P. and Rana, N.: Recent landslides in Uttarakhand: nature's fury or human folly, Curr. Sci. [online] Available from: https://www.researchgate.net/profile/Naresh_Rana/publication/285718177_Recent_landslides_in_Uttarakhand_Nature's_fury_or_human_folly/links/574e94cf08ae82d2c6be314c.pdf, 2011.

Schneider, A. and Woodcock, C. E.: Compact, Dispersed, Fragmented, Extensive? A Comparison of Urban Growth in Twenty-five Global Cities using Remotely Sensed Data, Pattern Metrics and Census Information, Urban Stud., 45(3), 659–692, doi:10.1177/0042098007087340, 2008.

Sepúlveda, S. A. and Petley, D. N.: Regional trends and controlling factors of fatal landslides in Latin America and the Caribbean, Nat. Hazards Earth Syst. Sci., 15(8), 1821–1833, doi:10.5194/nhess-15-1821-2015, 2015.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.

Sierra, J. P., Arias, P. A. and Vieira, S. C.: Precipitation over Northern South America and Its Seasonal Variability as Simulated by the CMIP5 Models, Advances in Meteorology, 2015, doi:10.1155/2015/634720, 2015.

Singh, R., Umrao, R. K. and Singh, T. N.: Stability evaluation of road-cut slopes in the Lesser Himalaya of Uttarakhand, India: conventional and numerical approaches, Bull. Eng. Geol. Environ., 73(3), 845–857, doi:10.1007/s10064-013-0532-1, 2014.

Soldati, M., Corsini, A. and Pasuto, A.: Landslides and climate change in the Italian Dolomites since the Late glacial, Catena, 55(2), 141–161, doi:10.1016/S0341-8162(03)00113-9, 2004.

Smyth, C. G. and Royle, S. A.: Urban landslide hazards: incidence and causative factors in Niterói, Rio de Janeiro State, Brazil, Appl. Geogr., 20(2), 95–118, doi:10.1016/S0143-6228(00)00004-7, 2000.

Srivastava, A., Goyal, C.R., Jain, A., Review of Causes of foundation failures and their possible preventive and remedial measures, in: Proceedings of 4th KKU- International Engineering Conference (KKU-IENC2012), Khon Kaen, Thailand, 10 – 12 May 2012, 2012.

Stanley, T. and Kirschbaum, D. B.: A heuristic approach to global landslide susceptibility mapping, Nat. Hazards, 87(1), 145–164, doi:10.1007/s11069-017-2757-y, 2017.

Taylor, F. E., Malamud, B. D., Freeborough, K. and Demeritt, D.: Enriching Great Britain's National Landslide Database by searching newspaper archives, Geomorphology , 249, 52–68, doi:10.1016/j.geomorph.2015.05.019, 2015.

Tedeschi, R. G., Cavalcanti, I. F. A. and Grimm, A. M.: Influences of two types of ENSO on South American precipitation, Int. J. Climatol., 33(6), 1382–1400, doi:10.1002/joc.3519, 2013.

The Economist, Rubies in the sky with diamonds: http://www.economist.com/node/21528623, last access: 20 February 2018, 2011.

Trenberth, K. E. and Shea, D. J.: Atlantic hurricanes and natural variability in 2005, Geophys. Res. Lett., 33(12), L12704, doi:10.1029/2006GL026894, 2006.

Tschoegl, L., Below, R., Guha-Sapir, D.: An analytical review of selected data sets on natural disasters and impacts, Centre for Research on the Epidemiology of Disasters, UNDP/CRED Workshop on Improving Compilation of Reliable Data on Disaster Occurrence and Impact, Bangkok, Thailand, 21 pp., 2006.

Turner, A. G. and Annamalai, H.: Climate change and the South Asian summer monsoon, Nat. Clim. Chang., 2, 587, doi:10.1038/nclimate1495, 2012.

UNESCO: Annual summary of information on natural disasters, no.6: 1971, United Nations Educational, Scientific and Cultural Organization, Paris, France, 82 pp., 1973

United Nations Statistics Division (UNSD): Standard country or area codes for statistical use, http://unstats.un.org/unsd/methods/m49/m49.htm, last access: 10/8/2016, 2018.

Valdiya, K. S.: Catastrophic Landslides in Uttaranchal, Central Himalaya, J. Geol. Soc. India, 52(4), 483–486 [online] Available from: http://52.172.159.94/index.php/jgsi/article/view/68951/54115 (Accessed 8 February 2018), 1998.

Van Den Eeckhaut, M. and Hervás, J.: State of the art of national landslide databases in Europe and their potential for assessing landslide susceptibility, hazard and risk, Geomorphology , 139-140, 545–558, doi:10.1016/j.geomorph.2011.12.006, 2012.

van Westen, C. J., Castellanos, E. and Kuriakose, S. L.: Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview, Eng. Geol., 102(3), 112–131, doi:10.1016/j.enggeo.2008.03.010, 2008.

Varnes, D. J. and IAEG Commission on Landslides: Landslide hazard zonation: a review of principles and practice: Paris, UNESCO, Paris, France, 63 pp., 1984

Webster, P. J., Magaña, V. O., Palmer, T. N., Shukla, J., Tomas, R. A., Yanai, M. and Yasunari, T.: Monsoons: Processes, predictability, and the prospects for prediction, J. Geophys. Res., 103(C7), 14451–14510, doi:10.1029/97JC02719, 1998.

World Bank, Transport: At a Glance, The World Bank, http://www.worldbank.org/en/topic/transport/overview, last access: 22/02/2018b.

World Bank, The World Bank data, https://data.worldbank.org/indicator/, last access: 19/02/2018a

Wu, X., Chen, X., Benjamin Zhan, F. and Hong, S.: Global research trends in landslides during 1991–2014: a bibliometric analysis, Landslides, 12(6), 1215–1226, doi:10.1007/s10346-015-0624-z, 2015.

Xie, P., Janowiak, J. E., Arkin, P. A., Adler, R., Gruber, A., Ferraro, R., Huffman, G. J. and Curtis, S.: GPCP Pentad Precipitation Analyses: An Experimental Dataset Based on Gauge Observations and Satellite Estimates, J. Clim., 16(13), 2197–2214, doi:10.1175/2769.1, 2003.

Yang, H., Xia, J., Thompson, J. R. and Flower, R. J.: Urban construction and demolition waste and landfill failure in Shenzhen, China, Waste Manag., 63, 393–396, doi:10.1016/j.wasman.2017.01.026, 2017.

Yang, F. and Lau, K.-M.: Trend and variability of China precipitation in spring and summer: linkage to sea-surface temperatures, International Journal of Climatology, 24(3), DOI: 10.1002/joc.1094, 2004.

Yu, K., Wang, S. and Li, D.: The negative approach to urban growth planning of Beijing, China, J. Environ. Planning Manage., 54(9), 1209–1236, doi:10.1080/09640568.2011.564488, 2011.

Zhang, F., Liu, G., Chen, W., Liang, S., Chen, R. and Han, W.: Human-induced landslide on a high cut slope: a case of repeated failures due to multi-excavation, Journal of Rock Mechanics and Geotechnical Engineering, 4(4), 367–374, doi:10.3724/SP.J.1235.2012.00367, 2012.

Zhou, T., Wu, B. and Dong, L.: Advances in research of ENSO changes and the associated impacts on Asian-Pacific climate, Asia-Pacific J Atmos Sci, 50(4), 405–422, doi:10.1007/s13143-014-0043-4, 2014.

Zou, F., Zhan, Q. and Zhang, W.: Quantifying the impact of human activities on geological hazards in mountainous areas: evidence from Shennongjia, China, Nat. Hazards, 90(1), 137–155, doi:10.1007/s11069-017-3039-4, 2018.

Tables

Table 1 Landslide trigger classification.

Classification	Definition	Keyword search terms
unknown	No trigger or obvious cause specified	-
rainfall	Rainfall raises pore-pressure in slope materials triggering failure.	"rain", "sleet", "storm", "hurricane", "precipitation", "flood", "water", "torrent"
earthquake	Strong ground motion associated with earthquakes weaken slope materials triggering failure (coseismic landslides).	"earthquake", "aftershock", "seismic", "tremor"
illegal mining	Unregulated or informal mining of slope materials in designated quarry or mine, where permission to extract material has not been granted.	"illegal", "permit", "regulat", "close", "informal", "pick", "illicit", "abandoned", "traditional", "license", "ban", "mine", "quarry", "spoil", "pit", "excavat"
illegal hillcutting	Hillcutting refers to the process of removing material from a hillslope for the purposes of altering its shape and/or to obtain slope material for use in construction, manufacture or farming. It is differentiated from mining, because it occurs on slopes that are not within a designated site of mining or quarrying, instead hillcutting typically occurs on individual slopes on steep agricultural land or on man-made slopes such as those along transport routes. Hillcutting differs from construction, because slope modification does not follow an engineering design to ensure slope stability. Hillcutting is assumed to be undertaken in an informal, unregulated manner (this is frequently noted in landslide reports)	"hillcut", "illegal", "permit", "regulat", "informal", "illicit", "traditional", "license", "ban", "excavat"
legal mining	Regulated and/or permitted mining of slope materials in designated quarry or mine, where permission to extract material has been granted and operations are managed.	"legal", "permit", "regulat", "pick", "license", "mine", "quarry", "spoil", "pit", "excavat"
mining (unknown)	Slope materials are extracted from a designated quarry or mine, but the report does not make it clear if the extraction is permitted or not.	"quarry", "mine", "spoil", "pit", "excavat"
construction	Permitted modification of a slope for the purposes of a construction project undertaken by professional labourers, following planning approval	"excavat", "construction", "site", "road", "build", "dig", "labour"
conflict and explosion	Landslide triggered by the detonation of an explosive device during military combat	"bomb", "mine", "soldier", "army", "explode", "explosion", "war", "conflict"
leaking pipe	Utility pipes carrying water that have been damaged and leak water onto a slope surface or within the hillslope, compromising its stability.	"pipe", "leak", "burst"
garbage collapse	Collapse of piles of municipal waste onto people, where stability of waste piles was disturbed by the passage of a person or persons	"waste", "trash", "rubbish", "garbage", "dump", "pick"
recreation	Triggered by passage of a person or persons walking/ climbing over a hillslope for recreation.	"climb", "mountain", "expedition", "ascent", "trek"
human action (unspecified)	Landslide report refers to a person or people present on a hillslope that collapses, without specifying the reason people occupied the slope or the landslide trigger	"people", "person", "men", "women", "children", "occup"
animal activity	Occupation of slope by animal triggering failure, either by weight and movement of animal on slope surface, or by burrowing within the slope subsurface.	"animal", "burrow", "tunnel"
fire	Naturally occurring or man-made fires, typically occurring in dry climates on vegetated terrain.	"fire"
natural dam or riverbank collapse	Collapse of a riverbank or natural dam without an apparent trigger, but likely caused by pore pressures building over time to a critical threshold in response to water levels. Material typically fails into a body of water, and often generates a flood wave.	"river", "bank", "dam", "earth", "flood", "wave", "collapse"
freezing	Heavy snowfall and expansion of water in hillslopes due to freezing, acting solely or together to destabilise the slope.	"snow", "extreme", "freeze", "ice", "cold"
freeze thaw (temperature change cold to hot), snowmelt	Failure of slope materials in response to temperature rise, including landslides triggered by the melting of snow or permafrost (in a non-volcanic setting)	"snow", "melt", "permafrost", "spring", "temperature"
volcanic eruption	Landslides (and mudflows) occurring in a volcanic environment triggered by volcanic activity- such as explosions and volcano-tectonic seismicity. This does not include events in active volcanic environments triggered by rainfall.	"volcan", "seismic", "activity", "eruption"
marine erosion	Triggered by sea erosion (only)- repeat wave impact	"coast", "sea", "erode"

Table 2. Spearman's rank correlation between mean daily rainfall and mean daily landslides by month (see Fig. 5).

Region	Correlation Coefficient	P value
Central America	0.8153	0.0012
South America	0.8062	0.0015
South East Asia	0.17	0.5974
South Asia	0.996	0
East Asia	0.9701	0

Table B1. Hierarchal linear regression results comparing the impact of seasonality in geographical regions with the global mean number of landslides per pentad through the annual cycle (see Fig. 4). The data series for each geographical region are sequentially added into the regression (such that the second row of the table is a regression of S.Asia + S.E. Asia with the global series).

Predictor Variables	**N (cumulative)**	**% (of total N)**	**R^2**	**ΔR^2**
+ S. Asia	1295	31.50	0.4962	
+ SE. Asia	2121	52.27	0.7365	0.2403
+ E. Asia	2804	71.88	0.8618	0.1253
+ S. America	3145	82.25	0.9129	0.0511
+ C. America	3340	88.03	0.9575	0.0446

Fig. 1

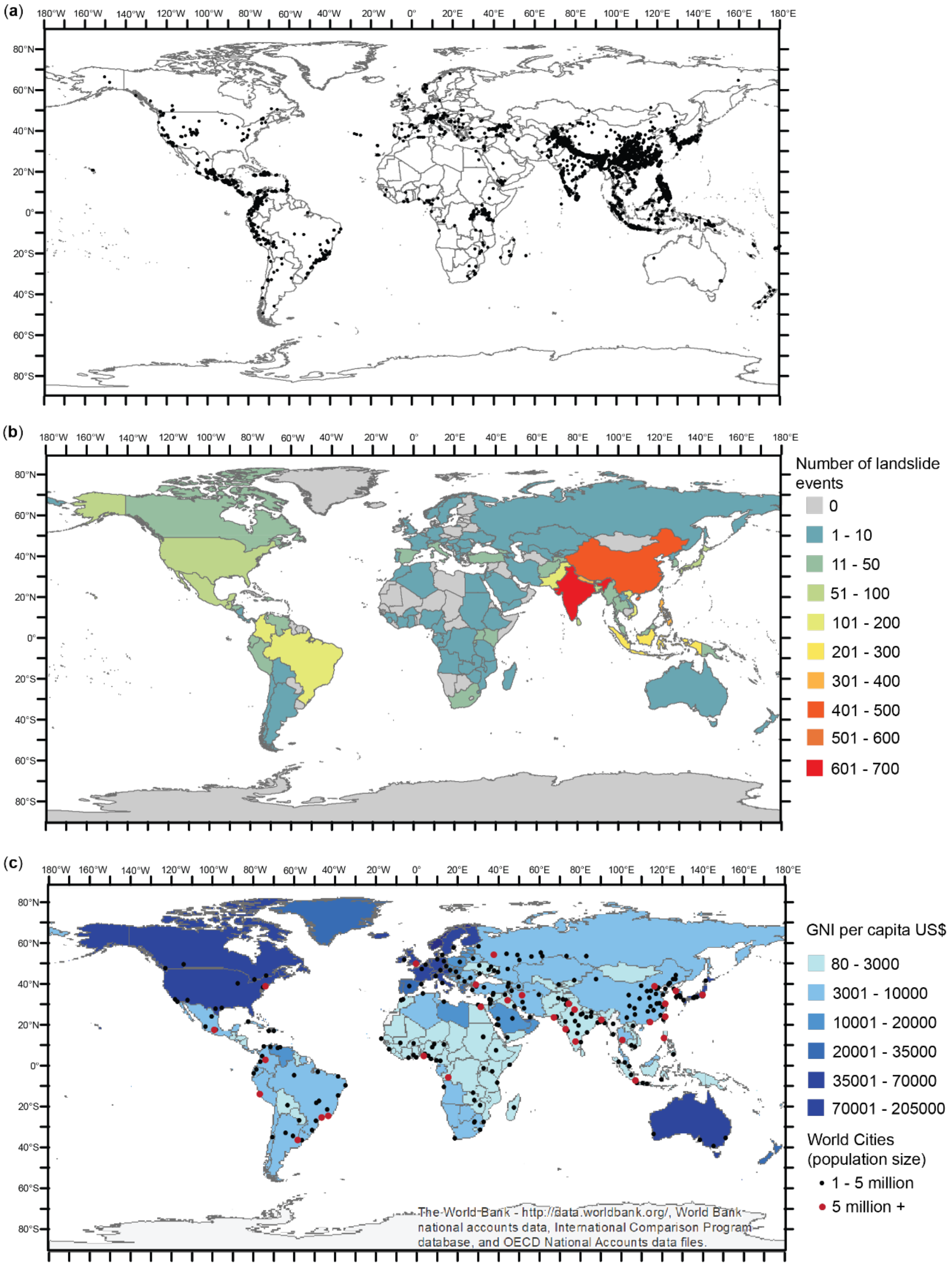
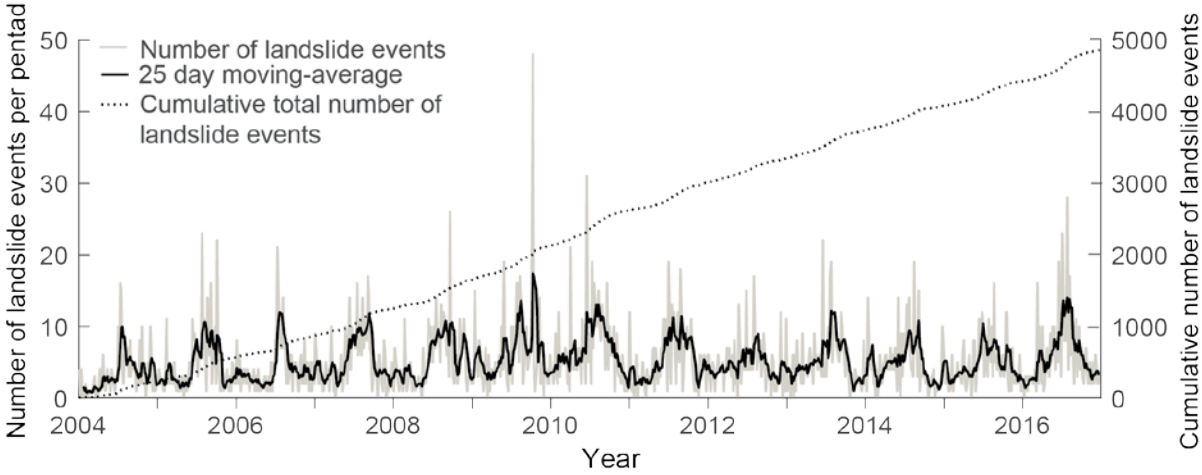
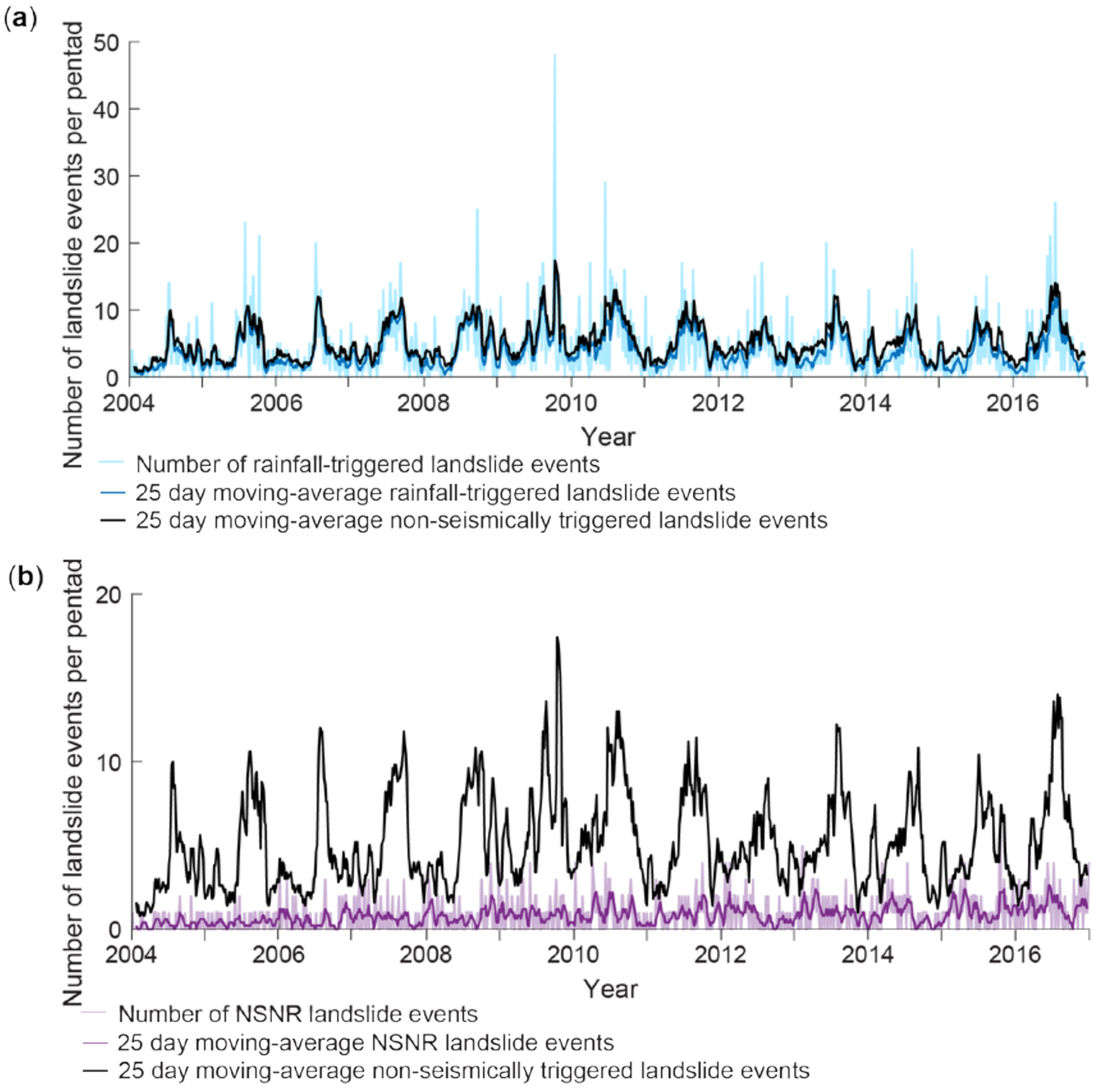

(a)
(b)
Number of landslide events
0
1 - 10
11 - 50
51 - 100
101 - 200
201 - 300
301 - 400
401 - 500
501 - 600
601 - 700
(c)
GNI per capita US$
80 - 3000
3001 - 10000
10001 - 20000
20001 - 35000
35001 - 70000
70001 - 205000
World Cities (population size)
1 - 5 million
5 million +
The World Bank - http://data.worldbank.org/, World Bank national accounts data, International Comparison Program database, and OECD National Accounts data files.

Fig. 2



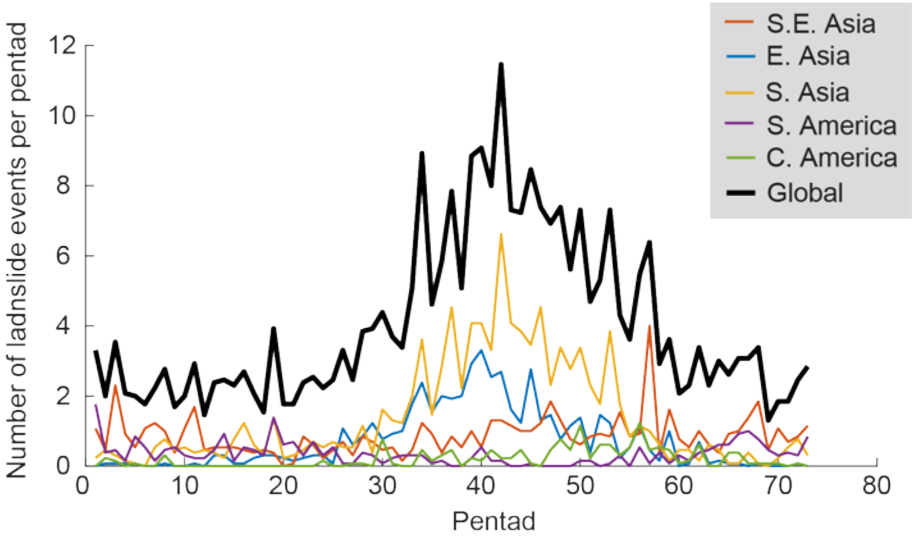
Number of landslide events
25 day moving-average
Cumulative total number of landslide events
Number of landslide events per pentad
Cumulative number of landslide events
Year
0
10
20
30
40
50
1000
2000
3000
4000
5000
2004
2006
2008
2010
2012
2014
2016

Fig. 3



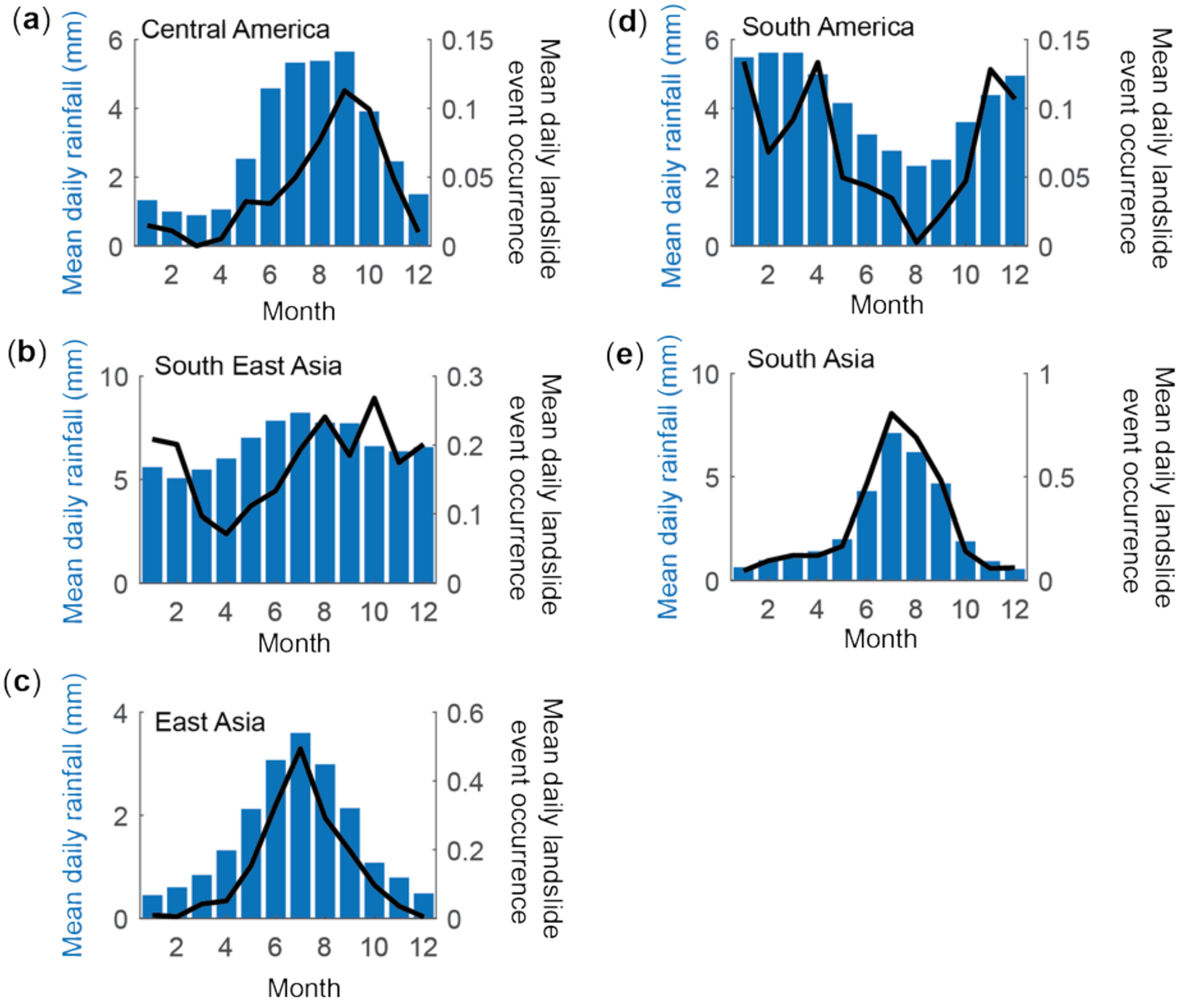
(a)
Number of landslide events per pentad
Year
Number of rainfall-triggered landslide events
25 day moving-average rainfall-triggered landslide events
25 day moving-average non-seismically triggered landslide events
(b)
Number of landslide events per pentad
Year
Number of NSNR landslide events
25 day moving-average NSNR landslide events
25 day moving-average non-seismically triggered landslide events

Fig. 4



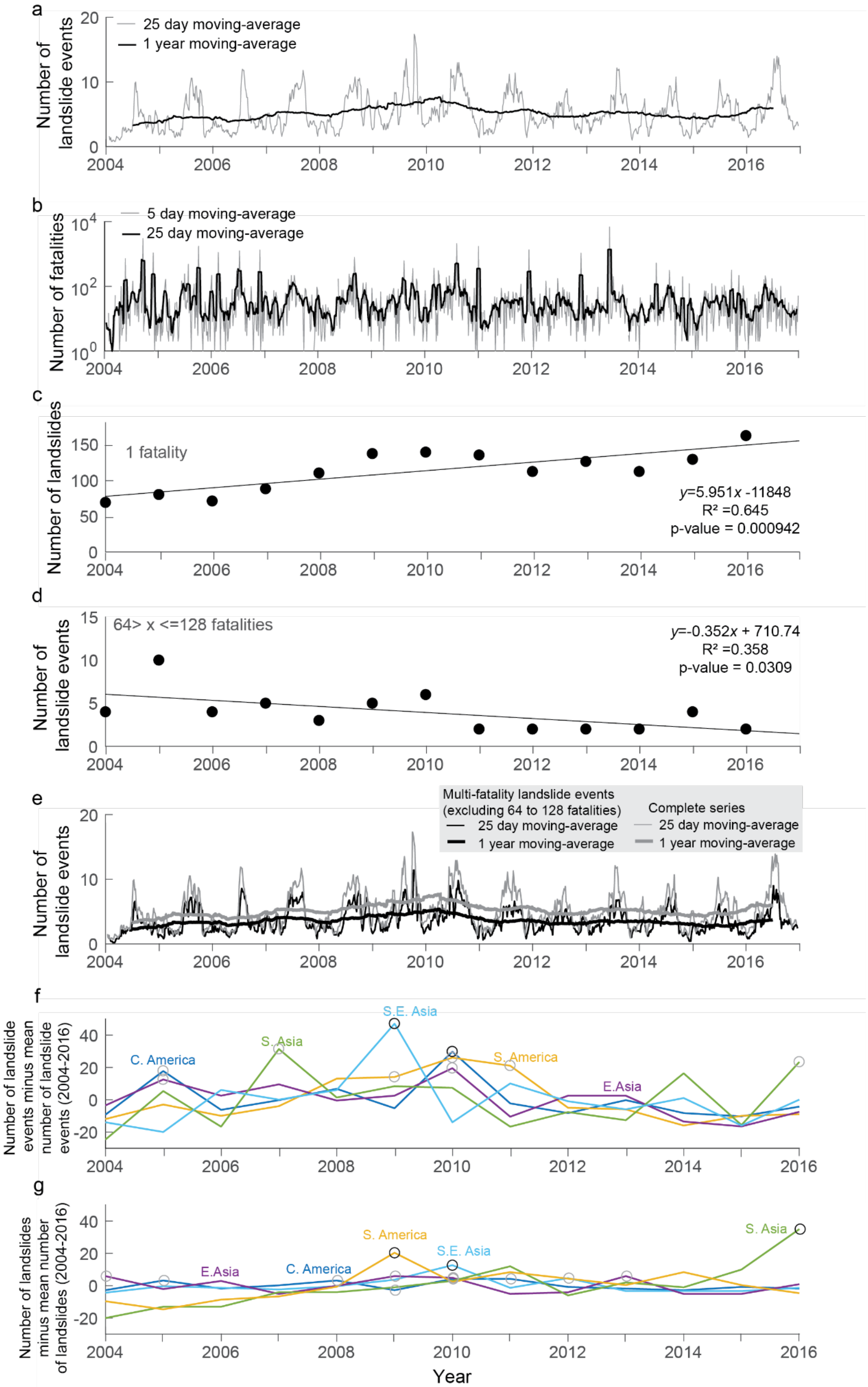
S.E. Asia
E. Asia
S. Asia
S. America
C. America
Global
Number of ladnslide events per pentad
Pentad

Fig. 5



(a) Central America
(b) South East Asia
(c) East Asia
(d) South America
(e) South Asia
Mean daily rainfall (mm)
Mean daily landslide event occurrence
Month

910 **Fig. 6**



a
Number of landslide events
25 day moving-average
1 year moving-average
b
Number of fatalities
5 day moving-average
25 day moving-average
c
Number of landslides
1 fatality
y=5.951x -11848
R² =0.645
p-value = 0.000942
d
Number of landslide events
64> x <=128 fatalities
y=-0.352x + 710.74
R² =0.358
p-value = 0.0309
e
Number of landslide events
Multi-fatality landslide events (excluding 64 to 128 fatalities)
25 day moving-average
1 year moving-average
Complete series
25 day moving-average
1 year moving-average
f
Number of landslide events minus mean number of landslide events (2004-2016)
S.E. Asia
S. Asia
C. America
S. America
E.Asia
g
Number of landslides minus mean number of landslides (2004-2016)
S. America
S. Asia
S.E. Asia
E.Asia
C. America
Year

911

Fig. 7

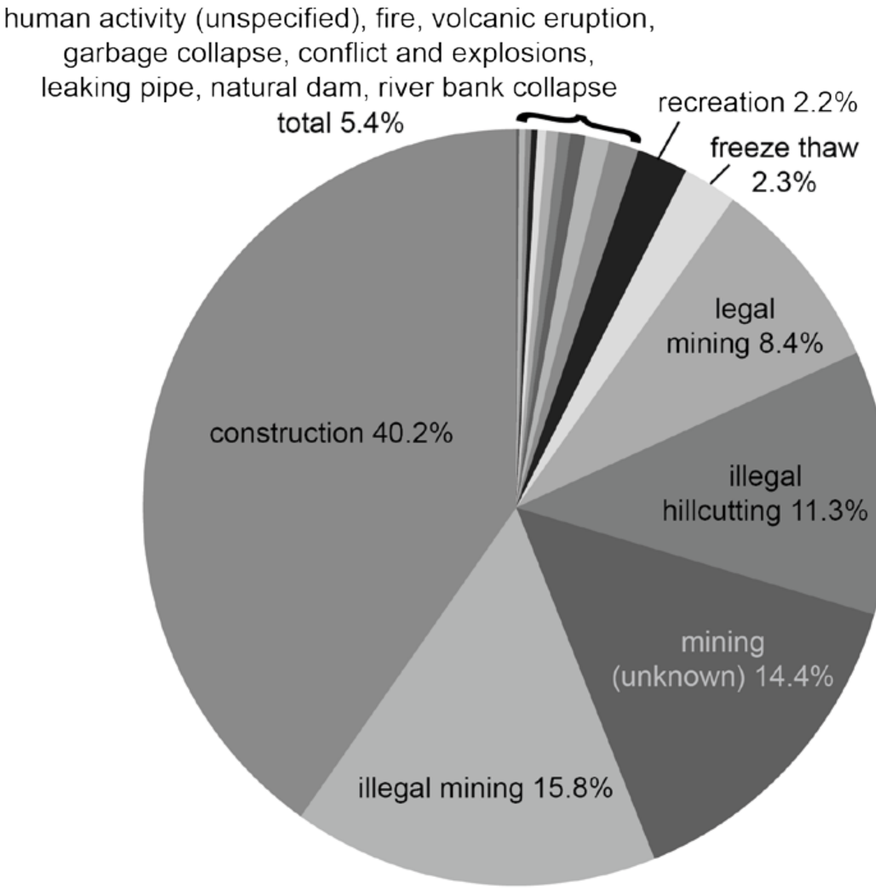

human activity (unspecified), fire, volcanic eruption, garbage collapse, conflict and explosions, leaking pipe, natural dam, river bank collapse total 5.4%
recreation 2.2%
freeze thaw 2.3%
legal mining 8.4%
illegal hillcutting 11.3%
mining (unknown) 14.4%
illegal mining 15.8%
construction 40.2%

Fig. 8

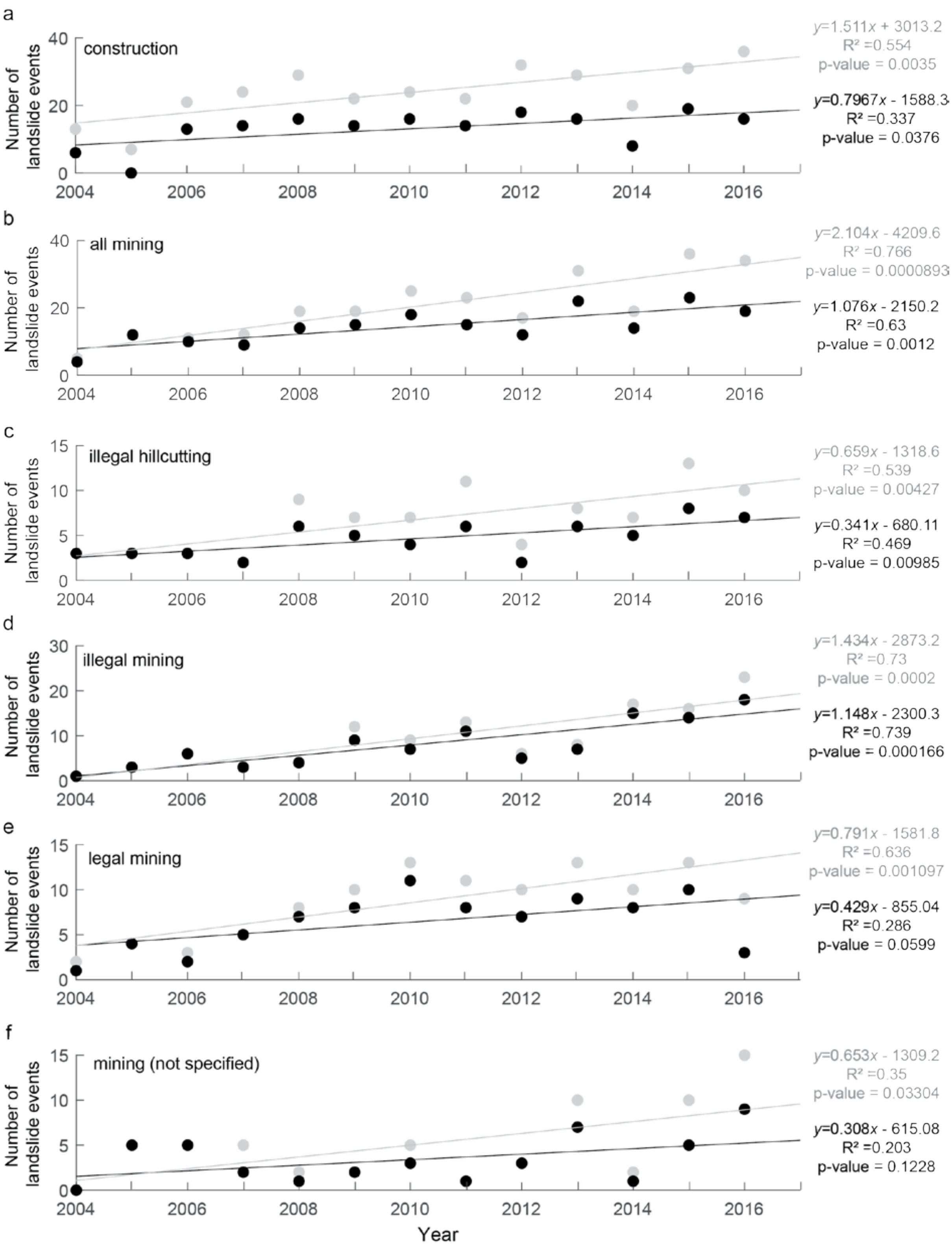
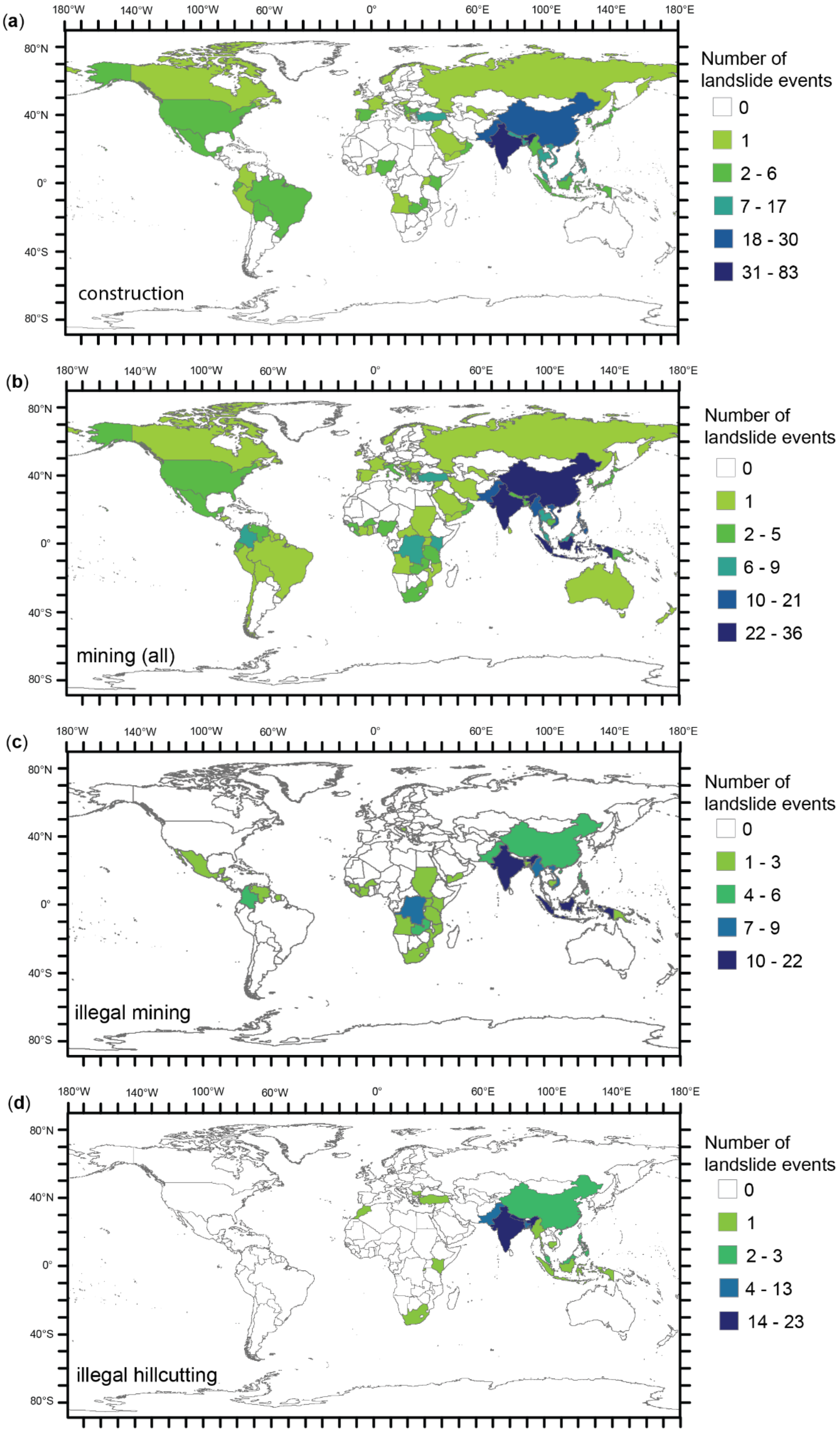

a
construction
Number of landslide events
y=1.511x + 3013.2
R^2 =0.554
p-value = 0.0035
y=0.7967x - 1588.3
R^2 =0.337
p-value = 0.0376
b
all mining
y=2.104x - 4209.6
R^2 =0.766
p-value = 0.0000893
y=1.076x - 2150.2
R^2 =0.63
p-value = 0.0012
c
illegal hillcutting
y=0.659x - 1318.6
R^2 =0.539
p-value = 0.00427
y=0.341x - 680.11
R^2 =0.469
p-value = 0.00985
d
illegal mining
y=1.434x - 2873.2
R^2 =0.73
p-value = 0.0002
y=1.148x - 2300.3
R^2 =0.739
p-value = 0.000166
e
legal mining
y=0.791x - 1581.8
R^2 =0.636
p-value = 0.001097
y=0.429x - 855.04
R^2 =0.286
p-value = 0.0599
f
mining (not specified)
y=0.653x - 1309.2
R^2 =0.35
p-value = 0.03304
y=0.308x - 615.08
R^2 =0.203
p-value = 0.1228
Year

Fig. 9



(a)
180°W
140°W
100°W
60°W
0°
60°E
100°E
140°E
180°E
80°N
40°N
0°
40°S
80°S
construction
Number of landslide events
0
1
2 - 6
7 - 17
18 - 30
31 - 83
(b)
mining (all)
Number of landslide events
0
1
2 - 5
6 - 9
10 - 21
22 - 36
(c)
illegal mining
Number of landslide events
0
1 - 3
4 - 6
7 - 9
10 - 22
(d)
illegal hillcutting
Number of landslide events
0
1
2 - 3
4 - 13
14 - 23

Appendix Figures

Fig. A1

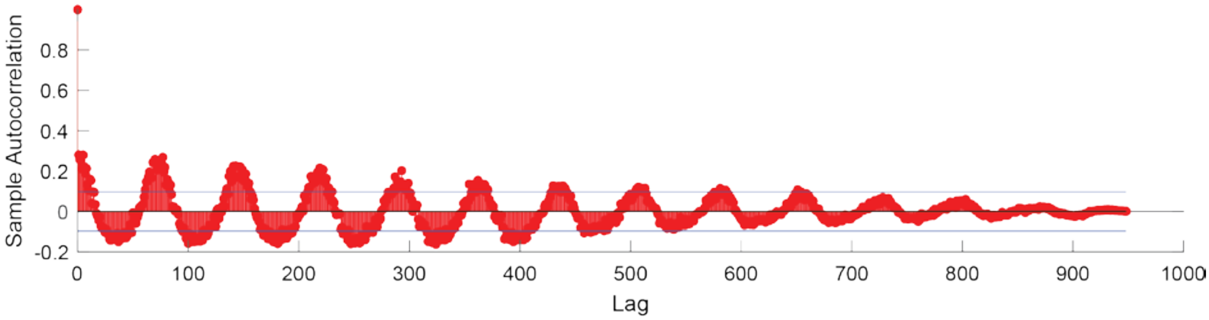


Fig. A2