



# Landslide risk reduction measures: A review of practices and challenges for the tropics

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### Abstract

The overall objective of this review is to gain insights into landslide risk reduction measures that are applied or recommended in tropical landslide-prone countries, and the challenges at play. More specifically, this review aims to (i) presenting an overview of recent studies on landslides and landslide risk reduction in these countries, (ii) exploring the factors controlling the publication output on landslides and landslide risk reduction, (iii) reviewing the various landslide risk reduction measures recommended and implemented, and (iv) identifying the bottlenecks for the implementation of these strategies. A compilation of recommended and implemented landslide risk reduction measures in 99 landslide-prone tropical countries was made, based on an extensive review of scientific literature (382 publications). The documented measures are analysed

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using a scheme of risk reduction measures that combines classifications of the Hyogo Framework for Action and the SafeLand project. Our literature review shows that the factors influencing the number of publications on landslides and landslide risk reduction per country are (in order of importance) the absolute physical exposure of people to landslides, the population number and the Human Development Index of a country. The ratio of publications on landslide risk reduction versus publications on landslides for landslide-prone tropical countries does not vary much between these countries (average: 0.28). A significant fraction (0.30) of all known landslide hazard reduction measures are neither implemented nor recommended according to our review. The most recommended landslide risk reduction component is 'risk management and vulnerability reduction' (0.38). However, the most implemented component is 'risk assessment' (0.57). Overall, the ratio of implemented versus recommended landslide risk reduction measures in the tropics is low (<0.50) for most landslide risk reduction components, except for 'risk assessment' (3.01). The most cited bottlenecks for implementing landslide risk reduction measures are scientific (0.30) and political (0.29) in nature.

### Keywords

Mass movements, disaster risk reduction, resilience, mitigation measures, Global South, tropical countries, research needs

## I Introduction

Landslides (LS) are defined as 'the movement of a mass of rock, debris or earth down a slope' (Cruden, 1991: 27). They present a serious problem in many regions worldwide, claiming thousands of deaths per year (Petley, 2012). Especially in the tropics, many regions are strongly affected by LS due to high precipitation and weathering rates, particularly in zones with steep topography and tectonic activity (Kirschbaum et al., 2015). Moreover, LS risk in the tropics is expected to increase in the near future as a response to increasing demographic pressure, deforestation and land use changes (Kjekstad, 2007) as well to climate change (Gariano and Guzzetti, 2016). In addition, most fatalities due to LS occur in Global South countries that are predominantly located within the tropics (Kirschbaum et al., 2015; Petley, 2012). Furthermore, the impact of LS on the population can be very high in tropical developing countries due to their high economic, social, political and cultural vulnerability (Alcántara-Ayala, 2002).

The recent Sendai Framework for Disaster Risk Reduction (DRR) has renewed the international focus on reducing risk of disasters (UNISDR, 2015). Investing in DRR was

identified as one of the key priorities. Disaster 'risk' is defined as 'the potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period' (UNISDR, 2009: 9), while 'hazard' refers to the natural event itself that may affect different places singly or in combination at different times (Wisner et al., 2004). According to UNISDR (2009: 10), DRR is 'the concept and practice of reducing disaster risks through systematic efforts to analyze and manage the causal factors of disasters, including through (i) reduced exposure to hazards; (ii) lessened vulnerability of people and property; (iii) wise management of land and the environment; and (iv) improved preparedness for adverse events'. Especially for low-intensity, high-frequency events like LS, DRR is considered the most cost-effective option to limit the negative impacts of disasters (Mechler et al., 2010).

It is relevant to first analyse what is currently being recommended and implemented globally to support research and investment in DRR (UNISDR, 2015). A hazard for which such a review of risk reduction (or mitigation) measures is still lacking is LS. As the scientific

literature on LS is rapidly increasing (Gutiérrez et al., 2010; Wu et al., 2015), it is important to maintain an overview, meaning that we understand which LS-DRR is being investigated and where, what explains observed differences between recommended and implemented measures and which potential pitfalls the implementation of such DRR is facing. Although such overview is certainly relevant to a wide audience, this is especially the case for earth scientists since most of the research on LS is currently conducted by this research community. A meta-analysis of recommended and implemented measures may certainly help in identifying the next steps to contribute to long-term LS-DRR.

The overall objective of this review is therefore to gain more insights into the implementation of LS-DRR measures applied and recommended in tropical LS-prone countries, and the challenges at play. We focus on the tropics for two reasons. First, this research frames in the AfReSlide project (Kervyn et al., 2015), which tries to identify LS-DRR measures for tropical countries such as Uganda and Cameroon. This study thus serves as a good starting point to understand LS-DRR in these two countries. Second, LS risk is expected to increase in tropical regions due to climate change, while many of these regions in Africa, South America and Asia are currently understudied (Gariano and Guzzetti, 2016). The projected increases in the intensity and frequency of extreme precipitation events in the tropics (IPCC, 2014) and subsequently on increasing LS risk (Seneviratne et al., 2012) serve as a valid reason to target tropical LS-prone countries for our analysis. The specific objectives are: (i) to compile an overview of studies on LS and LS-DRR in tropical LS-prone countries, (ii) to explore the factors controlling the number of scientific studies conducted on LS and LS-DRR per country, (iii) to review the various LS-DRR measures recommended and implemented and (iv) to identify the bottlenecks for implementing these measures.

## **II Study area, data and methods**

### *I Selection of study area and country-specific data*

In this study, we only considered countries for which (1) at least 50% of their land area lies between the tropical circles and (2) at least one inhabitant per year was exposed to either rainfall- or earthquake-triggered LS per year, according to the Global Risk Data collected by the Norwegian Geotechnical Institute (NGI) for the Global Assessment Report on DRR (Giuliani and Peduzzi, 2011). This Global Risk Data is, to our knowledge, the most complete and consistent global dataset. It expresses the absolute physical exposure to LS as the expected average annual population exposed (# inhabitants/year) and is based on the modelling of LS susceptibility and population density (NGI, 2013). Of the 138 tropical countries, 99 met this second criterion and were considered for our review on recommended and implemented DRR measures for LS (Table 1). Evidently, the Global Risk Data used to identify the LS-prone countries is subject to uncertainty. This uncertainty, combined with the relatively coarse spatial resolution of the data, may induce erroneous inclusions or exclusions in our list of tropical LS-prone countries. Especially, some small island states are not LS-prone according to this database, but this is not necessarily the case (Table 1); for example, the Bahamas (Buchan, 2000), the Seychelles (Payet, 2005), and St Vincent and the Grenadines (Anderson et al., 2010). Therefore, this list should be interpreted with caution. To investigate the potential extension of these errors, we also checked for each non-landslide-prone country to see whether articles on LS-DRR were published for that country (using the same methodology and criteria described in section 2.2). This was the case for nine countries (Table 1). However, given their small area, limited population and publication count, the impact of these wrongfully assigned countries on our analyses is likely to be very

**Table 1.** Overview of landslide-prone and non-landslide-prone tropical countries based on Global Risk Data (NGI, 2013) with, between brackets, the number of publications on landslides and on landslide risk reduction, respectively, in Scopus for the period between January 2005 and January 2015. An asterisk "\*" means that the countries do yield landslide publications in Scopus for the period between January 2005 and January 2015. (Note: Since the search period for articles was between January 2005 and January 2015, South Sudan was not considered.)

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Landslide-prone tropical countries ( $n = 99$ )

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Angola (4;1), Antigua and Barbuda (1;0), Bangladesh (20;10), Belize (0;0), Benin (1;0), Bolivia (17;5), Botswana (0;0), Brazil (154;39), Brunei (3;0), Burkina Faso (1;1), Burundi (1;0), Cambodia (4;1), Cameroon (17;4), Cape Verde (4;0), Cayman Islands (2;0), Central African Republic (0;0), Chad (0;0), Colombia (37;18), Comoros (2;1), Congo (7;0), Democratic Republic of Congo (4;1), Costa Rica (30;6), Cuba (8;3), Djibouti (0;0), Dominica (8;0), Dominican Republic (7;2), Ecuador (49;8), El Salvador (16;7), Equatorial Guinea (1;0), Eritrea (1;0), Ethiopia (19;6), Fiji (4;1), French Guiana (0;0), Gabon (0;0), Ghana (0;0), Grenada (4;1), Guadeloupe (10;3), Guam (0;0), Guatemala (15;3), Guinea (29;1), Guinea-Bissau (0;0), Guyana (1;1), Haiti (27;9), Honduras (15;8), India (430;139), Indonesia (97;35), Ivory Coast (0;0), Jamaica (7;2), Kenya (8;6), Laos (8;3), Liberia (2;0), Madagascar (4;1), Malawi (5;1), Malaysia (159;39), Mali (0;0), Martinique (8;1), Mauritius (1;0), Mexico (160;29), Mozambique (7;2), Myanmar (15;3), Namibia (3;1), Netherlands Antilles (0;0), New Caledonia (4;3), Nicaragua (26;5), Niger (4;2), Nigeria (19;3), Oman (9;1), Panama (14;2), Papua New Guinea (22;4), Paraguay (1;0), Peru (62;17), Philippines (71;23), Puerto Rico (37;8), Réunion (15;0), Rwanda ((2;0), São Tomé and Príncipe (0;0), Senegal (3;0), Sierra Leone (1;0), Solomon Islands (3;1), Somalia (2;1), Sri Lanka (21;11), St Lucia (5;4), Sudan (3;2), Suriname (0;0), Tanzania (6;2), Thailand (68;24), The Bahamas (4;1), The Gambia (0;0), Timor-Leste (0;0), Togo (0;0), Trinidad and Tobago (3;1), Uganda (18;4), Vanuatu (4;0), Venezuela (36;7), Vietnam (17;4), Virgin Islands (4;1), Yemen (6;3), Zambia (1;0), Zimbabwe (1;0)

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Non-landslide-prone tropical countries ( $n = 39$ )

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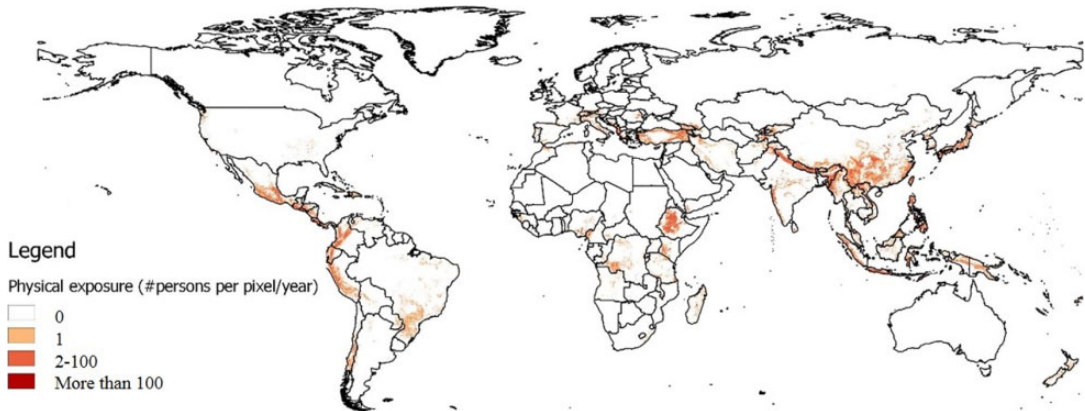
American Samoa, Anguilla, Aruba, Baker Island, Barbados\*, British Indian Ocean Territory, British Virgin Islands, Christmas Island, Cocos Islands, Cook Islands, French Polynesia\*, Glorioso Islands, Howland Island, Jarvis Island, Johnston Atoll, Juan De Nova Island, Kiribati, Maldives, Marshall Islands, Mauritania, Mayotte\*, Micronesia\*, Montserrat\*, Nauru, Niue, Northern Mariana Islands, Palau, Samoa\*, Seychelles\*, Singapore\*, St Helena, St Kitts and Nevis, St Vincent and the Grenadines\*, Tokelau, Tonga, Turks and Caicos Islands, Tuvalu, Wake Island, Wallis and Futuna

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limited. On the other hand, the Global Risk Data (NGI, 2013) provided an independent and objective criterion of countries to focus on. This helped us to avoid the possibility that our literature review was biased towards our prior knowledge of available literature. We therefore decided not to further correct or adapt our list of LS-prone countries and to focus our review on the tropical countries that were indicated as LS-prone based on the Global Risk Data (NGI, 2013).

In order to identify the factors controlling the application rate of LS-DRR measures, data on the Human Development Index (HDI) and the

physical exposure to LS were collected for each tropical LS-prone country ( $n = 99$ ). The HDIs of 2013 were collected from the Human Development report of 2014 (Malik et al., 2014). For 14 out of the 99 countries, data on HDI were not available. Most of these 14 countries are island states. The physical exposure of people to LS, i.e. the overlay of population density with LS susceptibility, was collected from the Global Risk Data of the NGI (NGI, 2013; Figure 1). The LS susceptibility depends on the slope gradient, lithology (or geology), soil moisture, vegetation cover, precipitation and seismicity (NGI, 2013). The population data were



**Figure 1.** World map with the absolute physical exposure of people to landslides, expressed as the expected annual average number of persons exposed in 2010, per pixel (5×5 km) (adapted from NGI, 2013).

retrieved from the UN Population Division and cover data of 2010, which was also used for the physical exposure (NGI, 2013). In order to obtain country-specific data, the physical exposure values for both precipitation- and earthquake-triggered LS were summed up for every pixel lying within the country's boundaries.

## 2 Compilation of scientific literature

Scopus<sup>®</sup> (Elsevier B.V., 2015) was chosen as the search engine to select articles for the detailed review on recommended and implemented LS-DRR measures. Initially, literature was searched using Web of Science<sup>™</sup> (WoS; Thomson Reuters, 2015), Google Scholar (Google, 2015) as well as Scopus because these search engines cover most published scientific literature (Falagas et al., 2007). Scopus, however, yielded the highest number of countries with publications and includes more social sciences-oriented publications besides natural sciences, which is deemed crucial for this research (Table 2). Furthermore, Scopus produces more citation counts than WoS (Bergman, 2012; Falagas et al., 2007) and it has been shown to result in fewer inconsistencies regarding content verification compared to

WoS and Google Scholar (Adriaanse and Rensleigh, 2013).

An inventory of peer-reviewed articles on LS and LS-DRR, published between January 2005 and January 2015, was thus made using Scopus. The keywords and Boolean search criteria described below were applied to the 'title', 'abstract' and 'keywords' simultaneously. In order to analyse the literature on LS-DRR, we first searched for publications on LS in general and then specifically publications on LS-DRR. For the LS literature, we used the following keywords and Boolean search criteria: <country name> AND (landslide\* OR 'mass movement' OR 'mass wasting'). For the LS-DRR literature, we used the same keywords and Boolean search criteria but added the terms 'prevention', 'management', 'mitigation', 'risk reduction' or 'remediation' in order to narrow down to DRR. Only peer-reviewed publications with English abstracts have been taken into account. An overview of the compiled literature is given in Table 2. Noteworthy is that 25% of the 536 publications concerns India. After detailed investigations, 154 out of the 536 LS-DRR publications were excluded because they were irrelevant for this research (e.g. articles on submarine LS). As a comparison, non-tropical LS-prone countries, like Italy and the USA yield respectively, 1529

**Table 2.** Number of publications on landslides (# pubs LS) and landslide risk reduction (# pubs LS-DRR) in the 99 tropical landslide-prone countries found in Scopus, Web of Science and Google Scholar for the period January 2005 to January 2015. The average number of publications per country (average #pubs/co), the median number of publications per country (median #pubs/co), the total number of publications (total #pubs) and the number of countries with publications (# countries with pubs) are also included. (Note: The keywords and Boolean search criteria were applied to the 'title', 'abstract' and 'keywords' simultaneously in the case of Scopus and WoS and to the 'title' of the publications in the case of Google Scholar as it is only possible to search in the entire body of text or only in the title. Patents were excluded from our search; NA = not applicable.)

		Average #pubs/co	Median #pubs/co	Total #pubs	# countries with pubs
Scopus (SC)	pubs LS (1)	20	4	1928	81
	pubs LS-DRR (2)	5	1	536	61
	Ratio (2)/(1)	0.25	0.25	0.28	NA
Web of Science (WoS)	pubs LS (1)	17	4	1715	78
	pubs LS-DRR (2)	3	0	340	44
	Ratio (2)/(1)	0.18	0	0.20	NA
Google Scholar (GS)	pubs LS (1)	8	0	753	46
	pubs LS-DRR (2)	1	0	68	19
	Ratio (2)/(1)	0.13	NA	0.09	NA

and 208 publications on LS and 294 and 37 publications on LS-DRR, using the same keywords and Boolean search.

Not all the research on LS-DRR in LS-prone tropical countries is published in peer-reviewed articles. To evaluate to what extent our review might be biased by the fact that only scientific peer-reviewed literature was considered, we conducted a much broader search, including 'grey literature', for Uganda. This country was chosen as a case-study due to an in-depth expertise by the authors and easy access to internal documents from national experts. Such access could not be obtained for the other countries studied. The grey literature considered includes reports of government institutions, non-governmental organisations (NGOs) and dissertations of national and foreign master students, retrieved through personal secondary data collection in Uganda and targeted search in Google. In total, 16 documents on LS-DRR were selected for Uganda in addition to the three peer-reviewed publications found

in Scopus. This grey literature is by no means exhaustive but representative judging from expert knowledge.

### *3 Factors explaining the number of publications on landslides and landslide risk reduction*

The initial search in Scopus resulted in 1928 LS publications and 536 LS-DRR publications (Table 2). Correlations between the number of publications and potential controlling factors, such as HDI, physical exposure to LS and population numbers, were searched for using the Spearman rank correlation ( $\rho$ ) as this method is not sensitive to outliers (Heinisch, 1962). In addition, we calculated Partial Spearman rank correlations (partial  $\rho$ ), which measures the degree of association between two considered variables, with the effect of one or more controlling variables removed (Heinisch, 1962). For these analyses, only the 85 countries having an available HDI were used.

## 4 Classifications

To examine the LS-DRR research output in the tropics, the compiled publications on LS-DRR were classified in terms of spatial scale of analysis, authors' country of origin, authors' organisation, and research discipline. For the spatial scale of analysis, the compiled publications were classified into six categories: local (e.g. cities, villages, roads and catchments), provincial (e.g. districts and states), national, regional and global (e.g. global scale highlighting a specific country as an example). For the authors' country of origin, the four categories are: national, foreign, mixed national and foreign, and unknown. For the authors' organisation, the six categories are: university, government, NGO, private sector, multiple organisations and unknown. For the research discipline, the journals and proceedings in which the publications were published were divided into four categories: natural science, social science, interdisciplinary and unknown.

To classify the LS-DRR measures, we used the general DRR classification suggested by Twigg (2007). This classification consists of five components: (i) risk management and vulnerability reduction, (ii) governance, (iii) knowledge and education, (iv) preparedness and response and (v) risk assessment. 'Risk management and vulnerability reduction' contain all measures related to reducing the occurrence of LS hazards, the vulnerability to LS and the exposure to LS. 'Governance' relates to institutional frameworks and policies on LS-DRR. 'Knowledge and education' consist of all measures related to awareness raising on LS. 'Preparedness and response' comprise all measures dealing with early warning and emergency response. 'Risk assessment' includes all aspects of understanding LS risk. These five components can then be further classified into specific risk reduction measures. The classification of LS-DRR has been the subject of much debate (Nadim and Lacasse, 2008). Here we used the

classification of the SafeLand project to further divide the component of 'risk management and vulnerability reduction' in subcategories (see section 3.2), since this was the most recent classification and since it was based on a comprehensive literature review (Vaciago, 2013). For a detailed description of specific LS-DRR measures, we refer to Twigg (2007) and Vaciago (2013).

Using this classification, the implemented and recommended LS-DRR measures in LS-prone tropical countries were identified by screening the abstract and conclusions of the 382 collected publications on LS-DRR in Scopus for the period January 2005 to January 2015. With implemented LS-DRR measures, we understand specific actions and techniques that are mentioned in the article (not necessarily with detailed explanation) as currently being developed or operational. Similarly, with recommended measures we mean specific actions and techniques that are suggested as recommendations (not necessarily with detailed explanation) but not yet developed or operational in the country.

Finally, the bottlenecks for implementing LS-DRR measures have been identified by screening the abstract and conclusions of the 382 publications. After identification, these bottlenecks were classified into six sections based on our own judgement: i.e. scientific, political, social, economic, disaster risk management related and geographic bottlenecks. All categories are, however, not mutually exclusive.

## III Results and discussion

### *I Analysis of the number and nature of publications*

*1.1 Factors explaining the number of publications on landslides and on landslide risk reduction.* Several factors influence the number of publications on LS per country (#pubs LS/co; Table 3 and Figure 2).

**Table 3.** Correlations (Spearman rho's with \* $p < 0.01$ ; \*\* $p < 0.001$ ) between the number of publications per country on landslides (# pubs LS/co) and on landslide risk reduction (# pubs LS-DRR/co), and the Human Development Index of a country (HDI/co) (Malik et al., 2014), the absolute physical exposure of people to landslides per country (NGI, 2013), the relative physical exposure of people to landslides per country (NGI, 2013), and the national population in 2010 (UN, 2010) ( $n = 85$  landslide-prone countries, for which the HDI is available).

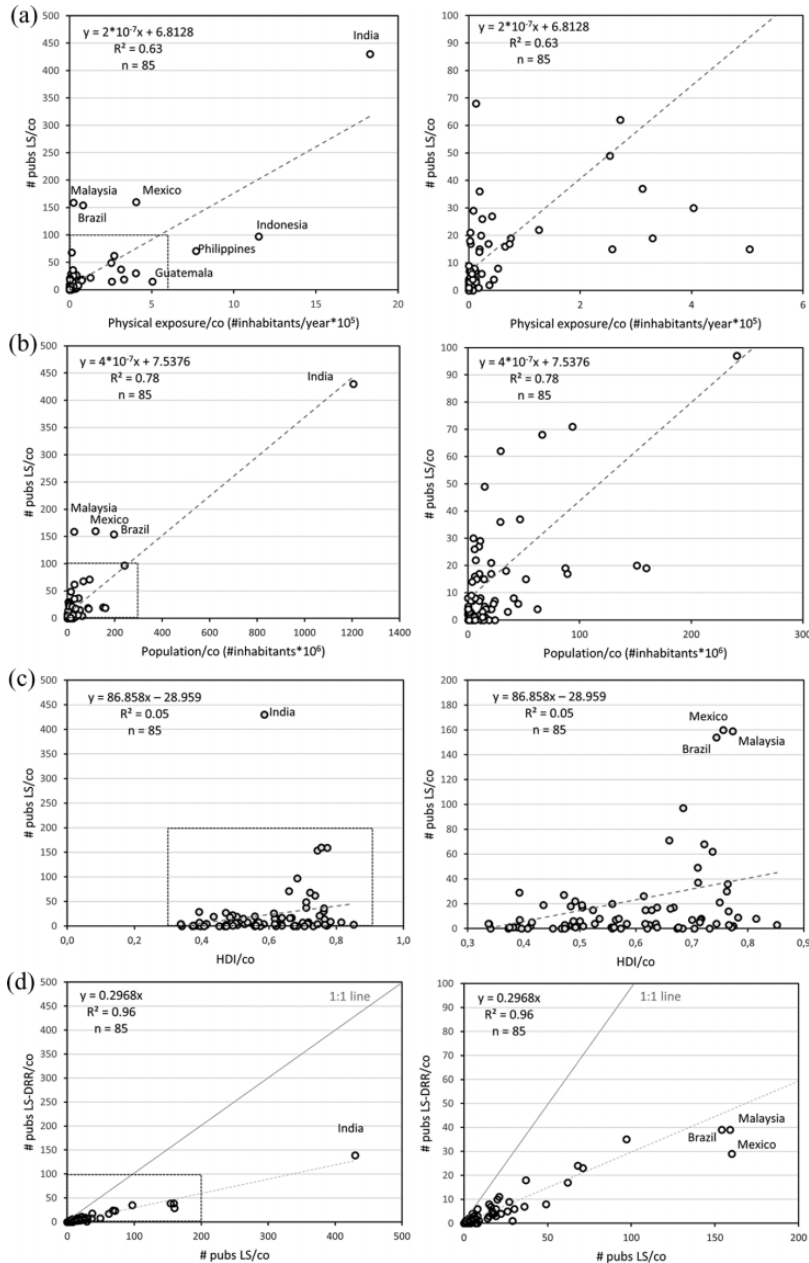
	HDI/co	Absolute physical exposure/co (#inhabitants/year)	Population/co (#inhabitants)	#pubs LS-DRR/co	Relative physical exposure/co (#exposed inhabitants/#inhabitants/year)
#pubs LS/co	0.35**	0.77**	0.55**	0.90**	0.49**
#pubs LS-DRR/co	0.32*	0.73**	0.61**		
Population/co (#inhabitants)	-0.17	0.52**			
Absolute physical exposure/co (#inhabitants/year)	0.19				

The #pubs LS/co best correlates with the absolute physical exposure of people to LS per country ( $\rho = 0.77$ ,  $p < 0.001$ ; Table 3), which suggests that countries with a larger exposed population (e.g. Philippines in comparison with Guatemala) are generally more concerned about LS (Figure 2a). This is, of course, assuming that the number of publications reflects the level of concern. High risk perception does not necessarily result into more preparedness, however, as indicated by Wachinger et al. (2013). The partial correlation between the absolute physical exposure and the #pubs LS/co remains significant after controlling for the effect of the other controlling variables, i.e. HDI (partial  $\rho = 0.77$ ,  $p < 0.001$ ) and population (partial  $\rho = 0.68$ ,  $p < 0.001$ ). The countries with the relatively lowest LS publication count per exposed citizen are Indonesia, Philippines, Guatemala, Costa Rica, Ethiopia, Colombia, India and Myanmar, while Malaysia and Brazil have the highest publication count – absolute physical exposure ratio (Figure 2a). Noteworthy is that the #pubs LS/co is also correlated with the relative physical exposure, i.e. the people exposed to LS per country divided by the total population per country ( $\rho = 0.49$ ,  $p < 0.001$ ; Table 3).

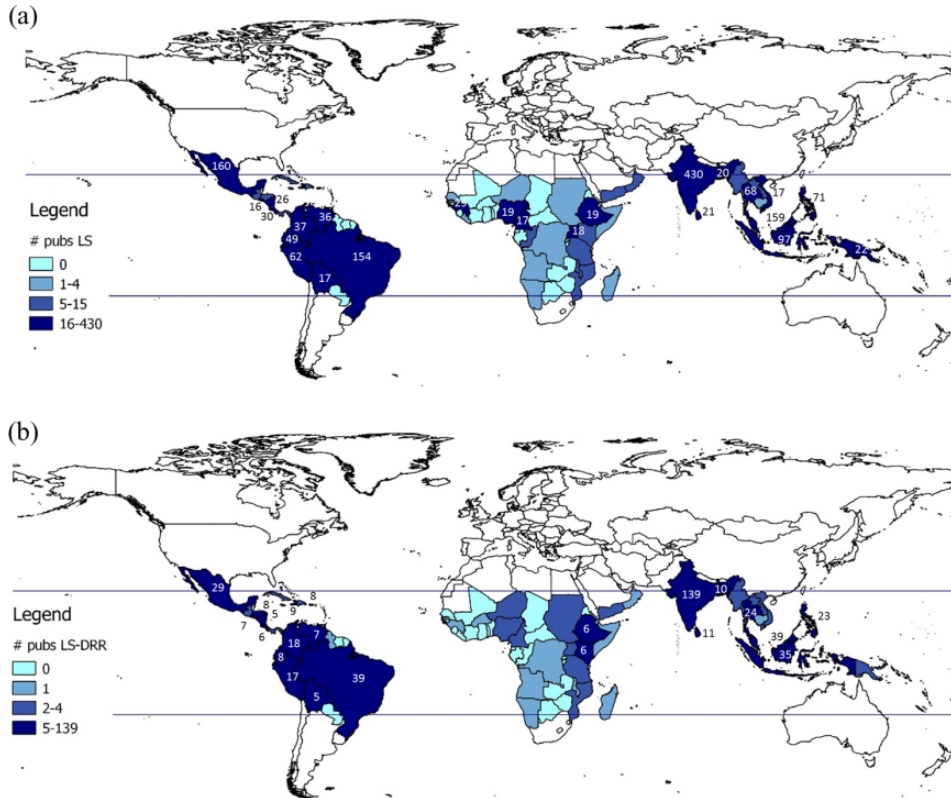
The #pubs LS/co is also correlated with population ( $\rho = 0.55$ ,  $p < 0.001$ , Figure 2b; Table 3). The Spearman rank is smaller for the correlation with population than with the absolute physical exposure per country, despite the lower coefficient of determination. This correlation remains significant after removing the effect of the other controlling variables, i.e. absolute physical exposure of people to LS (partial  $\rho = 0.28$ ,  $p < 0.01$ ) and HDI (partial  $\rho = 0.67$ ,  $p < 0.001$ ).

The third most important determining factor is the HDI of a country ( $\rho = 0.35$ ,  $p < 0.001$ ; Figure 2c; Table 3). This correlation remains significant after removing the other controlling variables, i.e. the absolute physical exposure of people to LS (partial  $\rho = 0.34$ ,  $p < 0.01$ ) and population per country (partial  $\rho = 0.55$ ,  $p < 0.001$ ). This correlation suggests that countries with a high HDI have more resources to support scientific research, including on LS. This is in line with the correlation made by Petley (2012) indicating that, globally, countries with the highest #pubs LS/co have generally lower numbers of fatalities. However, this correlation is relatively weak and clearly less significant than the absolute physical exposure to LS.





**Figure 2.** Scatter plots of the factors determining the number of publications on landslides per country (#pubs LS/co) in Scopus for the period January 2005 to January 2015 ( $p < 0.001$ ;  $n = 85$ ) indicating the linear trend line and the coefficient of determination, (a) the absolute physical exposure of people to landslides (# inhabitants/year) of the tropical landslide-prone countries, (b) the population (# inhabitants) of the tropical landslide-prone countries, (c) the HDI of the tropical landslide-prone countries, and (d) the number of publications on landslide risk reduction (# pubs LS-DRR) of the tropical landslide-prone countries. The figures on the left present the entire dataset, while the figures on the right correspond to the zoom (indicated with a box in the figures on the left). (Note: Visual outliers are labelled.)

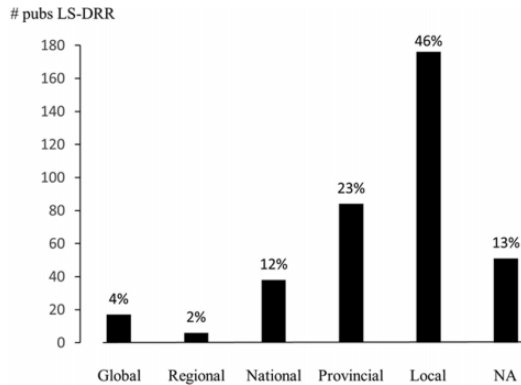


**Figure 3.** (a) World map with the number of publications on landslides (# pubs LS) reported in Scopus of the tropical landslide-prone countries for the period January 2005 to January 2015, and (b) World map with the number of publications on landslide risk reduction (# pubs LS-DRR) reported in Scopus of the tropical landslide-prone countries for the period January 2005 to January 2015. Numbers indicate the # pubs for countries with more than 15 publications (for pubs LS) and more than four publications (for pubs LS-DRR).

Finally, it is noteworthy that the number of publications on LS-DRR per country (# pubs LS-DRR) are strongly correlated with the #pubs LS/co ( $\rho = 0.90$ ,  $p < 0.001$ , Figure 2d; Table 3). The ratio between the two variables is rather constant, even when the outlier (India) is excluded. Given this strong correlation, it is not surprising that none of the factors considered here (i.e. HDI, population and physical exposure) correlated significantly with the ratio between LS-DRR and LS. In fact, this strong correlation implies that this ratio is relatively constant ( $\sim 0.3$ ) over the countries considered. As a comparison, this ratio is 0.19 and 0.17 for the non-tropical LS-prone countries Italy and the USA, respectively.

**1.2 Nature of publications on landslide risk reduction.** On average, there are 20 publications on LS per country and five publications on LS-DRR (Table 2). Figure 3 shows the number of publications on LS and LS-DRR per tropical LS-prone country for the period January 2005 to January 2015. Overall, these maps indicate that especially larger countries in Asia and South America (e.g. India and Brazil) have a high number of publications on LS and LS-DRR, while most African countries clearly have less peer-reviewed literature on these subjects.

The LS-DRR literature from Scopus is described in detail in the following paragraphs. In terms of spatial scale, the largest number of



**Figure 4.** Number of publications on landslide risk reduction (# pubs LS-DRR) of tropical landslide-prone countries in Scopus for the period January 2005 to January 2015 grouped according to the spatial scale of analysis ( $n = 382$ ; NA = not available).

the 382 consulted publications are local (176 publications), while articles focusing on a provincial scale form the second largest group (88 publications; Figure 4). The third largest group consists of studies for which the spatial scale could not be clearly identified (51 publications).

Overall, up to 52% of all the 382 publications involve scientists from the country of interest. This percentage is clearly smaller for Africa and Latin America than for Asia and the Pacific (Figure 5). Interestingly, a relatively large percentage of the publications involve only foreign institutions (24%). In African and Latin American countries, publications conducted by only foreign institutions form the largest group (42% and 36%, respectively). Knowing that only 6% of the compiled articles concerns LS in Africa, this indicates that the number of African scientists publishing on LS is very small.

Universities employ the largest percentage of authors (41%). In Africa, however, a fairly large percentage is connected to a NGO (25%), while collaborative research between different types of actors is also common (38%; Figure 6).

The literature on LS-DRR is dominated by natural sciences, as 65% of the articles was published in a ‘natural science’ journal or

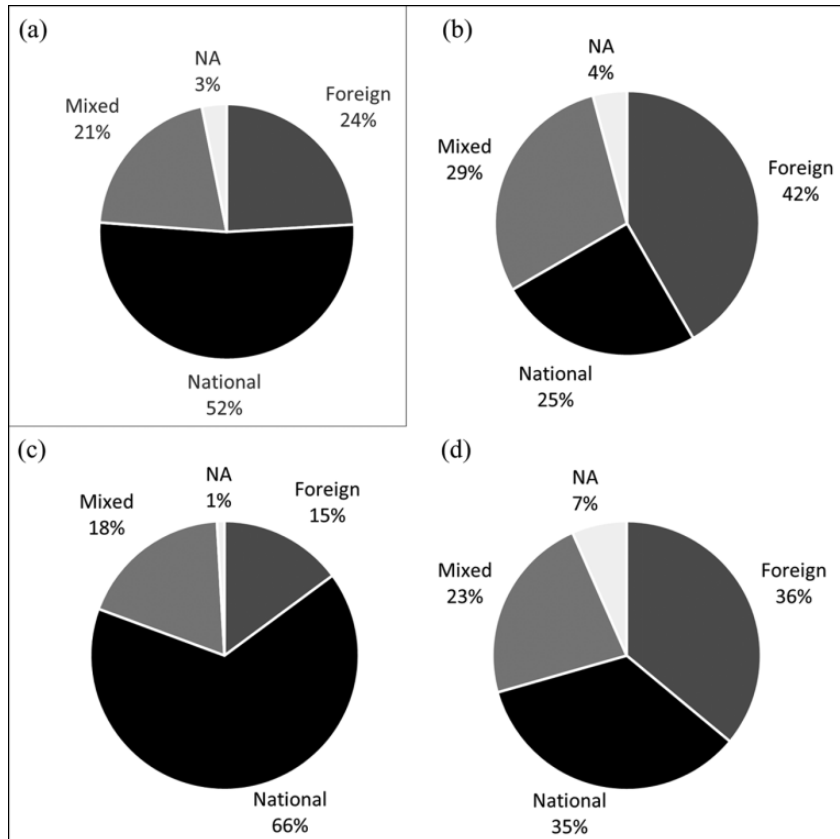
proceedings volume, 19% in an ‘interdisciplinary’, only 2% in a ‘social science’ and 14% in a journal or proceedings volume of unknown research discipline.

## 2 Overview of landslide risk reduction measures

Of all LS-DRR measures, ‘LS risk assessment’ is by far the most implemented DRR component (57%), while ‘risk management and vulnerability reduction’ is the most recommended DRR component (38%; Figure 7). ‘LS risk assessment’ is the most implemented component in all regions, but receives relatively more attention in Africa (72%), which might be attributed to the fact that landslide hazard research is still emerging on this continent and that governance remains a challenge for the implementation of other DRR actions (UNISDR, 2012). While ‘LS risk management and vulnerability reduction’ is the most recommended component in all tropical regions, it receives somewhat less attention in Asia-Pacific (27%) as compared to Africa (40%) and Latin America (42%). Generally, implemented and recommended measures vary relatively little between different regions.

Overall, 575 LS-DRR measures were cited as being implemented in 304 articles, while 906 measures were recommended in 279 articles (Table 4). In the following sections, each LS-DRR component is described in detail: first, by stating the most recommended measures, second, the most implemented measures and, third, by explaining their implementation/recommendation ratio.

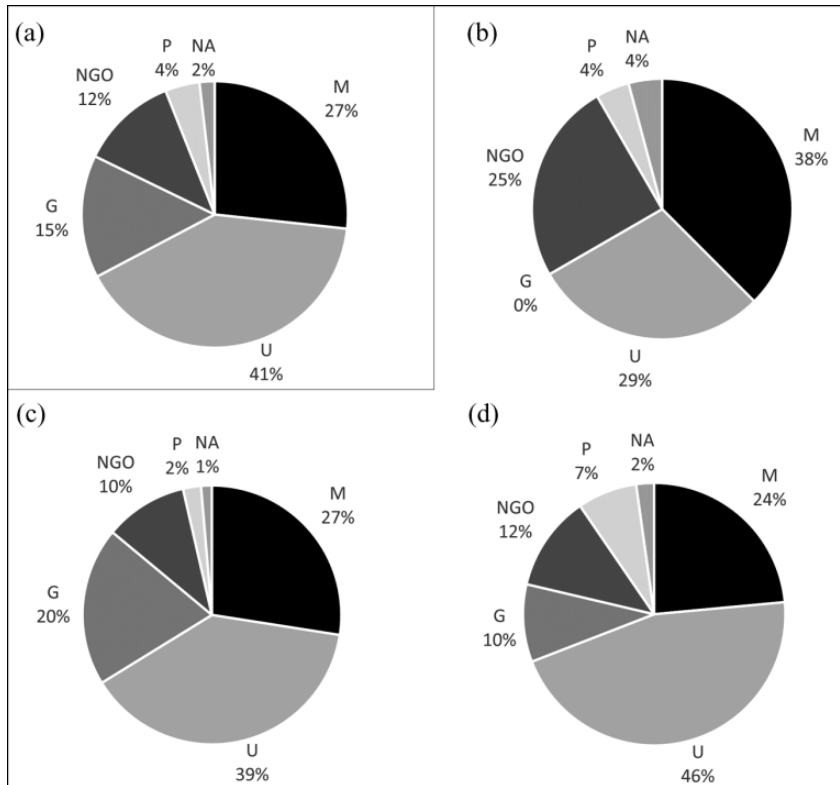
Noteworthy is that the main focus of landslide research remains on ‘hazard’ assessment. This focus might be explained by the fact that disaster research is rooted in the natural sciences (Watts, 1983). Our review also indicates that implemented LS-DRR measures are dominantly focusing on the collection of ‘hazard’ instead of ‘vulnerability’ data. Of the 255 publications citing the implementation of



**Figure 5.** Distribution of the number of publications on landslide risk reduction (# pubs LS-DRR) in Scopus for the period January 2005 to January 2015 according to the authors' country of origin, (a) Tropics ( $n = 382$ ), (b) Africa ( $n = 24$ ), (c) Asia-Pacific ( $n = 222$ ) and (d) Latin America ( $n = 136$ ) (NA = not available).

'collection of hazard/risk data and assessment' (Table 4), 236 publications refer to the collection of 'hazard' data, while only 19 cite the collection of 'risk' data. This focus on understanding hazards in disaster research is, however, gradually shifting towards understanding vulnerability and loss of resilience to disasters (Manyena et al., 2013). Our review shows that this shift is indeed increasingly being recommended but not yet reported as implemented. Similarly, most publications focusing on the combination of both hazard and vulnerability, i.e. risk, are relatively new (69% of these studies were published in 2010 or later).

**2.1 Risk management and vulnerability reduction.** 'Risk management and vulnerability reduction' is the most recommended component (38%, 342 publications) while being among the least implemented component (15%, 84 publications; Table 4; Figure 7). This component faces the least progress of all DRR components for all hazards globally (UNISDR, 2013). Our review suggests the same for LS in tropical LS-prone countries despite being highly recommended. The fact that LS risk management and vulnerability reduction is highly recommended might be because it involves LS-specific actions whereas others are valid for all hazards.



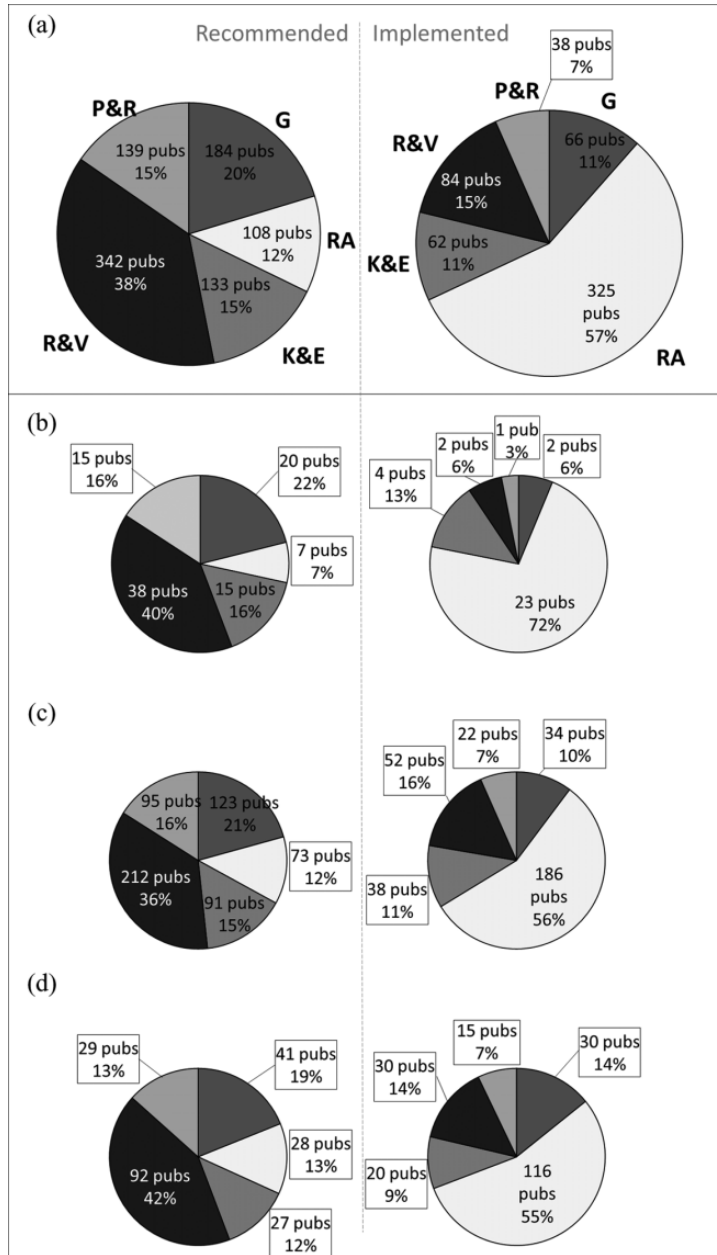
**Figure 6.** Distribution of the publications on landslide risk reduction (# pubs LS-DRR) in Scopus for the period January 2005 to January 2015 according to the authors' organisation, (a) Tropics ( $n = 382$ ), (b) Africa ( $n = 24$ ), (c) Asia-Pacific ( $n = 222$ ) and (d) Latin America ( $n = 136$ ) (U = university, G = government, NGO = non-governmental organisation, P = private sector, NA = not available, M = multiple organisations).

For the 'risk management and vulnerability reduction' component, a list of specific actions for each category of our combined classification is provided in Table 5, based on the SafeLand project that presents the most recent classification and is based on a comprehensive literature review (Vaciago, 2013). Table 5 illustrates that many measures listed by the SafeLand project are neither implemented nor recommended, e.g. expensive measures like drainage tunnels and deep mixing with lime and/or cement. This indicates that, although complete, this classification is too comprehensive for LS-prone tropical countries.

Risk zoning for land use planning is mostly recommended and implemented in the literature

for the tropics (117 and 15 publications, respectively) followed by bio-engineering techniques (32 and 6 publications, respectively; Table 5). Noteworthy as well is the recommendation and implementation of the modification of the surface water regime (39 and 15 publications, respectively).

'LS risk management and vulnerability reduction' has a relative low implementation/recommendation ratio, i.e. 0.25 (Table 4). Similarly, Anderson et al. (2014) state that the implementation of LS hazard reduction measures, also known as remedial or slope stabilisation measures, is limited in many tropical regions mainly because of the perceived high costs.



**Figure 7.** Percentage of the number of publications on landslide risk reduction (# pubs LS-DRR) in Scopus for the period January 2005 to January 2015 that cite the recommended landslide risk reduction components (left column) and the implemented landslide risk reduction components (right column) (see Table 4). (a) Total percentages of the number of publications reporting recommended (total number of citations is 709, reported in 225 individual papers) and implemented landslide risk reduction components (total number of citations is 461, reported in 245 individual papers). Subfigures (b–d) show these results for the specific sub-regions.

**Table 4.** Number of publications (#pubs) in Scopus for the period January 2005 to January 2015 that cite implemented (I) and recommended (R) landslide risk reduction (LS-DRR) measures in tropical landslide-prone countries (see Table 1). According to Twigg (2007), 'early warning systems' are part of the preparedness and response component, while according to Vaciago (2013), these are part of exposure reduction measures and thus the risk management and vulnerability reduction component. As some publications cite several measures, a difference is made between the total number of cited LS-DRR measures (total # citations) and the total number of individual publications that cite LS-DRR measures (total # individual pubs) (NA = not applicable).

DRR component	Landslide risk reduction measures	I		R		I/R
		#pubs	%	#pubs	%	
Governance (G)		66	11	184	20	0.36
	Policy, planning, priorities and political commitment	13	2	34	4	0.38
	Legal and regulatory systems	1	0	14	2	0.07
	Integration with development policies and planning	2	0	21	2	0.1
	Integration with emergency response and recovery	3	0	3	0	1
	Institutional mechanisms, capacities and structures; allocation of responsibilities	24	4	63	7	0.38
	Partnerships	9	2	12	1	0.75
	Accountability and community participation	14	3	37	4	0.38
Risk assessment (RA)		325	57	108	12	3.01
	Unspecified	8	2	31	3	0.26
	Collection of hazard/risk data and assessment	255	44	59	7	4.32
	Assessment of vulnerability/capacity and impact data	52	9	15	2	3.47
	Scientific and technical capacities and innovation	10	2	3	0	3.33
Knowledge and education (K&E)		62	11	133	15	0.47
	Public awareness, knowledge and skills	11	2	62	7	0.18
	Information management and sharing	31	5	35	4	0.89
	Education and training	13	2	24	3	0.54
	Cultures, attitudes, motivation	3	1	2	0	1.5
	Learning and research	4	1	10	1	0.4
Risk management and vulnerability reduction (R&V)		84	15	342	38	0.25
	Unspecified	3	1	27	3	0.11
	Landslide hazard reduction	2	0	19	2	0.11
	Unspecified	7	1	49	6	0.14
	Surface protection; erosion control of landslide-toe					
	Modifying the geometry and/or mass distribution	2	0	13	2	0.15
	Modifying surface water regime	15	3	39	4	0.38
	Modifying groundwater regime	4	1	8	1	0.5
	Modifying the mechanical characteristics of unstable mass	2	0	1	0	2
	Transfer of loads to more competent strata	2	0	5	1	0.4
	Retaining structures	12	2	22	2	0.55
Vulnerability reduction	Measures to improve capacities of people to cope with landslides	7	1	21	2	0.33

(continued)

**Table 4.** (continued)

DRR component	Landslide risk reduction measures	I		R		I/R
		#pubs	%	#pubs	%	
	Measures to increase the resistance of critical infrastructures	5	1	1	0	5
	Measures to stop or to deviate the path of landslides	2	0	3	0	0.67
Exposure reduction	Measures to decrease number of elements at risk potentially affected	16	3	121	13	0.13
	Relocation and migration	5	1	13	2	0.38
Preparedness and response (P&R)		38	7	139	15	0.27
	Unspecified	1	0	21	2	0.05
	Early warning systems	36	7	74	8	0.49
	Risk transfer (insurance)	0	0	10	1	0
	Organisational capacities of and coordination by local communities	0	0	6	1	0
	Contingency planning	1	0	14	2	0.07
	Emergency resources and infrastructures	0	0	9	1	0
	Emergency response and recovery by local communities	0	0	3	0	0
	Participation, voluntarism, accountability	0	0	2	0	0
Total # citations		575	100	906	100	0.63
Total # individual pubs		304		279		1.09

**2.2 Governance.** Governance is cited as the second most recommended LS-DRR component (20%, 184 publications; Table 4; Figure 7). Likewise, it is the second most implemented component (11%, 66 publications). This strong attention for governance might be explained by the strong emphasis of the Hyogo Framework for Action (HFA) on nations as prime actors for setting up DRR measures (Twigg, 2007). Since the ratification of the HFA in 2005, disaster governance is put forward as a key priority (UNISDR, 2015).

The most commonly recommended and implemented governance actions are the improvement of institutional mechanisms, capacities and structures and the allocation of responsibilities (63 and 24 publications, respectively; Table 4). The latter includes improving coordination and communication in LS risk management and improving capacities at all policy levels. These capacities vary largely

between different tropical countries, according to the level of decentralisation, the availability of resources and the political-administrative structure (Maskrey, 2011).

The ratio of implemented and recommended measures is, with an average value of 0.36, rather low (Table 4). The measures with a clearly higher ratio are the integration of LS-DRR with emergency response and recovery (1.00) and creating partnerships (0.75). Partnerships between countries and within countries can be between the government and other stakeholders such as NGOs, the private sector and research institutes. Especially since the HFA in 2005 and the first World Landslide Forum (WLF) in 2008, several international partnerships have been established including regional networks of the International Consortium on LS in Latin America (Alcántara-Ayala et al., 2014), Asia (Billedo et al., 2013) and to a lesser extent in Africa (e.g. Igwe, 2013). Other examples are the



**Table 5.** Landslide risk management and vulnerability reduction measures as suggested by the SafeLand project (Vaciago, 2013). The number of publications on landslide risk reduction (# pubs LS-DRR) in Scopus for the period January 2005 to January 2015 recommending (R) a specific ‘risk management and vulnerability reduction’ measure to reduce landslide risk (total number of citations is 342, reported in 169 individual publications) and describing that a specific ‘risk management and vulnerability reduction’ measure to reduce LS risk is being implemented (I) (total number of citations is 84, reported in 52 individual publications).

Landslide risk reduction measures	# pubs LS-DRR		Countries
	I	R	
Unspecified	3	27	I: Mexico, Sri Lanka, St. Lucia R: Bangladesh, India, Indonesia, Kenya, Malaysia, Mexico, Myanmar, Nicaragua, Oman, Peru, Philippines, Sri Lanka, St Lucia, Tanzania, Thailand, Venezuela, Yemen
Landslide hazard reduction	46	156	
Unspecified	2	19	I: Malaysia R: Ethiopia, India, Malaysia, New Caledonia
Surface protection; erosion control	7	49	
Unspecified	0	15	R: Bolivia, Brazil, Ethiopia, India, Indonesia, Kenya, Malaysia, Mexico, Nigeria, Sri Lanka, Thailand
Bio-engineering techniques (hydropseeding, turfing, trees/ bushes)	6	32	I: Ecuador, Guatemala, Honduras, India, Philippines, R: Bolivia, Brazil, Ecuador, Guatemala, Haiti, India, Indonesia, Kenya, Mexico, Nigeria, Philippines, Thailand, Sri Lanka
Geosynthetics	1	2	I: India R: India
Not mentioned (Fascines/brush; Drainage blanket; Beach replenishment, rip-rap; Dentition)			
Modifying geometry and/or mass distribution	2	13	
Removal of material from area driving the landslide	1	6	I: India R: Bolivia, India, Kenya, Mexico
Addition of material to area maintaining stability	1	5	I: Bolivia R: Bolivia, Kenya, Nigeria
Reduction of general slope angle	0	1	R: India
Scaling	0	1	R: India
Modifying surface water regime	15	39	
Unspecified	4	17	I: Bangladesh, Bolivia, Malaysia, Peru R: Bangladesh, Bolivia, Brazil, Cameroon, Ethiopia, India, Kenya, Malaysia, Mexico, Nigeria, Puerto Rico
Diversion channels	2	5	I: India R: India, Indonesia, Mexico
Check dams	1	3	I: India R: India, Philippines
Surface drains to divert flows from slide area	7	9	I: India, St Lucia R: Bolivia, Cameroon, Honduras, India, Philippines, St Lucia
Sealing tension cracks	0	1	R: India

(continued)

**Table 5.** (continued)

Landslide risk reduction measures	# pubs LS-DRR		Countries
	I	R	
Impermeabilisation	1	2	I: India R: Kenya, Mexico
Vegetation	0	2	R: Haiti, Kenya
Modifying groundwater regime	4	8	
Unspecified	0	5	R: India, Kenya, Mexico
Shallow or deep trenches with free-draining geo-materials and synthetics	2	0	I: India
Sub-horizontal drains	1	3	I: India R: Honduras, India
Wells and caissons	1	0	I: Philippines
Not mentioned (Drainage tunnels, galleries, adits)			
Modifying mechanical characteristics of unstable mass	2	1	
Compaction	1	0	I: Malaysia
Permeation or pressure grouting with cementitious or chemical binders	0	1	R: India
Jet grouting	1	0	I: Philippines
Not mentioned (Substitution; Deep mixing with lime and/or cement; Modification of groundwater chemistry)			
Transfer of loads to more competent strata	2	5	
Shear keys, barrettes and caissons	1	2	I: Peru R: India, Peru
Anchors: soil nails, dowels, rock bolts, multi-strand anchors	1	2	I: India R: India, Philippines
Anchored walls	0	1	R: India
Retaining structures	12	22	
Unspecified	2	13	I: India R: Cameroon, India, Kenya, Malaysia, Mexico, Philippines
Gravity walls (e.g. masonry, mass concrete and gabions)	5	4	I: India, Mexico, Peru R: Peru, India
Reinforced soil systems	5	5	I: India, Laos, Malaysia, Peru, Thailand R: Bolivia, India, Malaysia, Mexico, Peru
Not mentioned (Cantilever walls)			
Vulnerability reduction	14	25	
Measures to increase resistance of critical infrastructures	5	1	
Strengthening of shallow foundations and improved structural design	5	1	I: Colombia, Ecuador, Philippines R: Cameroon
Not mentioned (Deep anchoring with or without foundation elements)			

(continued)

**Table 5.** (continued)

Landslide risk reduction measures	# pubs LS-DRR		Countries
	I	R	
Measures to stop or to deviate path of the landslide	2	3	
Re-modelling of the slope	1	0	I : India
Planting vegetation on slope	1	1	I : India R : Brazil
Rockfall sheds	0	2	R : Colombia
Not mentioned (Diversion channels; Catch trenches; Rockfall barriers; Rockfall nets or drapery)			
Measures to improve capacities of people to cope with landslides	7	21	
Unspecified	1	10	I: Indonesia R: Bolivia, Dominican Republic, India, Indonesia, Mexico, Sri Lanka, Thailand
Improve human capital (knowledge sharing, education, health)	2	5	I: Bolivia, Uganda R: India, Kenya, Mexico
Improve social capital (social relations)	1	1	I: Costa Rica R: Bangladesh
Improve financial capital	3	5	I : Bolivia, India, Uganda R: Bangladesh, India, Malaysia, Mexico
Not mentioned (Improve natural and physical capital)			
Exposure reduction	21	134	
Measures to decrease number of elements at risk	16	121	
Risk zoning for land use planning	15	117	I: Brazil, Colombia, Costa Rica, El Salvador, Honduras, India, Indonesia, Malaysia, Sri Lanka R: Bangladesh, Bolivia, Brazil, Cameroon, Colombia, Dominican Republic, El Salvador, Ethiopia, Guatemala, Honduras, India, Indonesia, Kenya, Malaysia, Mexico, Myanmar, Nicaragua, Oman, Panama, Peru, Philippines, Puerto Rico, Sri Lanka, Tanzania, Thailand, Venezuela, Yemen
Traffic restrictions	1	4	I : India R: India
Relocation and migration	5	13	I: Dominican Republic, El Salvador, Haiti, India R: Bangladesh, Brazil, Cameroon, Honduras, India, Peru, Thailand

Multi-national Andean Project in seven Latin American countries (Jaramillo, 2008), the Disaster Research Nexus for collaborative research in Malaysia (Koh et al., 2012) and the Integrated Disaster Risk Management Plans for 12 provinces within Vietnam (Long et al., 2010). The

measure with a relatively low implementation/recommendation ratio is the integration of DRR with development policies and planning (0.10). This low rate is in line with the call of the Sendai Framework for a common ‘sustainable development’ and DRR agenda (UNISDR, 2015).

**2.3 Knowledge and education.** Knowledge and education is among the least recommended (15%, 133 publications) and least implemented LS-DRR components (11%, 62 publications; Table 4; Figure 7). Nevertheless, literature suggests that it serves as a prerequisite for the implementation of any other measure (Wamsler et al., 2012).

The main recommendations for this DRR component are public awareness in combination with the improvement of knowledge and skills (62 publications), information management and sharing (35 publications) and education and training (24 publications; Table 4). For example, in Guatemala awareness on how to detect early warning signs is recommended (Santi et al., 2011). Because local people are the first actors after a LS occurs, their role in DRR cannot be underestimated (Parkash, 2013). It is therefore recommended that especially local people should be targeted in awareness campaigns related to LS-DRR (e.g. in Sri Lanka: Dias et al., 2013). Remarkably, cultural and individual behaviour receive very limited attention altogether although perception and cultural representation of risk have been reported to be essential in the implementation of DRR (Cannon and IFRC, 2014).

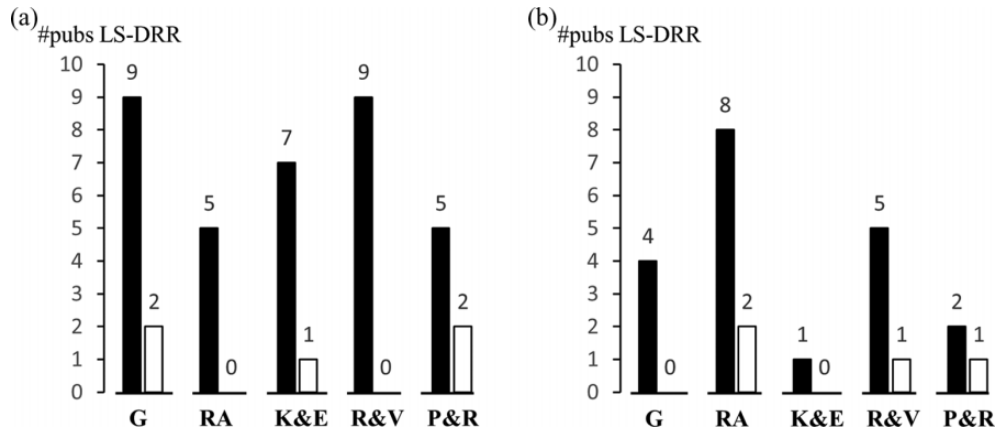
Knowledge and education has a moderate implementation/recommendation ratio, i.e. 0.47 (Table 4). Cultures, attitudes and motivation has a high ratio (1.50). This measure includes studying motivations for adopting measures and using indigenous knowledge for DRR. Information management and sharing has a relatively higher ratio (0.89) and includes the development of web-based or GIS tools for data collection as well as the development of guidelines for implementation of LS-DRR measures. Education and training also has a relatively higher ratio (0.54). Examples are the inclusion of LS-DRR topics in the university curricula and the training of officials on LS-DRR. A national education programme on LS has been introduced in Bangladesh (Ali et al., 2014), Colombia (Hermelin and Bedoya, 2008), India

(Parkash, 2013), Malaysia (Abdullah, 2013), Sri Lanka (Bandara and Weerasinghe, 2013) and in Vietnam (Long et al., 2010). A distinctly small number of studies discuss the implementation of public awareness schemes and improvement of knowledge and skills on LS-DRR, despite the fact that this action is highly recommended (0.18) and the positive effects of such DRR actions (e.g. Shaw et al., 2009). This could be partly attributed to the limited involvement of scientists in this type of actions (Cutter et al., 2015).

**2.4 Preparedness and response.** Preparedness and response to LS events is among the least recommended components (15%, 139 publications) while also being the least cited implemented DRR component (7%, 38 publications; Table 4; Figure 7).

The main recommended and implemented measures belonging to this DRR component are recognising physical signs that LS might occur in the near future (e.g. development of tension cracks), warning and subsequent evacuation (74 and 36 publications, respectively) and contingency planning to a limited extent (14 and 1 publications, respectively; Table 4). Examples of measures such as implementing contingency plans (Scolobig et al., 2014) and temporary relocation (Gorokhovich et al., 2013) are fairly isolated. No scientific publications could be found on the evaluation of LS emergency response and recovery, coordination, response resource and infrastructures nor the involvement of volunteers.

Preparedness and response measures have a relatively low implementation/recommendation ratio, i.e. 0.27 (Table 4). Only early warning systems (EWS) have a higher ratio (0.49). For an overview of EWS in South East Asia we refer to Billedo et al. (2013) and to Larsen (2008) for EWS in general. LS are predicted based on monitoring earthquakes and rainfall events (Bandara et al., 2013) or applying LS prediction models, e.g. in Indonesia (Liao et al., 2011), and



**Figure 8.** Number of publications on landslide risk reduction (# pubs LS-DRR) reporting (a) recommended and (b) implemented landslide risk reduction (LS-DRR) components (see Table 4) for Uganda based on grey literature and peer-reviewed literature on landslide risk reduction in Scopus (black bars) or based on peer-reviewed literature only (white bars), (G = governance, RA = risk assessment, K&E = knowledge and education, R&V = risk management and vulnerability reduction, P&R = preparedness and response).

through community-based reporting systems, e.g. in the Philippines (Marciano et al., 2011). LS monitoring is often considered as an effective and even affordable measure for DRR and has helped to reduce the number of fatalities in several countries during recent years, e.g. in Sri Lanka (Bandara et al., 2013).

Interestingly, risk insurance is not often recommended despite an internationally growing interest for its general implementation (UNISDR, 2013). This lack is most probably due to the fact that risk insurance is less profitable for low-intensity, high-frequency events like LS as losses might be covered more effectively domestically (Mechler et al., 2010) and because of a lack of formal insurance markets in many rural areas in the tropics. Nevertheless, Anderson and Holcombe (2013) argue that social funds, i.e. informal insurance based on social relations, play a major role in the tropics and increasingly focus on the vulnerability component of LS-DRR (e.g. Mertens et al., 2016).

**2.5 Risk assessment.** Risk assessment is the least recommended (12%, 86 publications) but most implemented LS-DRR component (57%, 262

publications; Table 4; Figure 7). This might be attributed to the fact that risk assessment is considered the first step towards LS risk management (Crozier and Glade, 2005; DeGraff, 2012), which can also be seen in our literature review from the fact that 53% of recommended measures are made in case risk assessment was already implemented. The large focus on scientific knowledge about LS cannot only be attributed to the fact that we restrict this review to peer-reviewed scientific literature, as a comparison with literature including grey literature for Uganda shows that the preference for implementing LS risk assessment is visible in both reviews (Figure 8).

Within this DRR component, the most frequently reported LS risk assessment techniques are the collection and analysis of LS susceptibility, hazard and risk data (59 publications for recommendation, 255 publications for implementation) including LS susceptibility and hazard mapping (124 publications for implementation) and the compilation of LS inventories (61 publications for implementation; Table 4). LS susceptibility mapping involves the classification and spatial distribution of current and potential LS in a certain area, while LS hazard

mapping adds an estimated frequency to the potential LS (Fell et al., 2008). LS risk mapping goes further by taking the outcomes of the hazard mapping and assessing the potential damage to persons, private property and infrastructure (Fell et al., 2008). The fact that the latter is more complicated explains why LS risk mapping is less implemented than susceptibility and hazard mapping (16 versus 97 publications). A systematic procedure for assessing LS risk at national scale is in most cases lacking (but not necessarily desirable), except for countries such as Brazil (Soler et al., 2013), Cuba (Abella and van Westen, 2007), India (van Westen et al., 2012), Malaysia (Abdullah, 2013) and Vietnam (Long et al., 2010). Important to note here is that an exclusive promotion of LS susceptibility maps for landslide risk zoning, without site-specific hazard assessments for diagnosis and design of landslide hazard reduction measures, might potentially lead to a lack of effective LS mitigation on the ground (Anderson et al., 2014). For an extensive review on current landslide susceptibility mapping methodologies we refer to the LAMPRE project (Malamud et al., 2014).

LS risk assessment has a high implementation/recommendation ratio, i.e. 3.01 (Table 4). Especially scientific and technical capacities and innovation have a very high ratio (4.32). Noteworthy is that the only scientific and technical innovation cited in literature is the identification of rainfall thresholds that might trigger LS. Countries where rainfall thresholds have been identified are: Ecuador (Ibadango et al., 2007), India (Bhusan et al., 2014), Jamaica (Miller et al., 2009), Malaysia (Althuwaynee et al., 2014), Mexico (Antinao and Farfan, 2013) and Puerto Rico (Wieczorek and Leahy, 2008).

### ***3 Bottlenecks for implementation of landslide risk reduction measures***

Despite the increased literature on LS-DRR measures (Gutiérrez et al., 2010; Wu et al.,

2015), we show that the implementation of measures and their scientific documentation remains rather scarce in the tropics. Furthermore, the low implementation/recommended ratio of most LS-DRR components and difference between recommended and implemented measures suggest that implementing LS-DRR measures remains challenging in the tropics. As their implementation involves different actors and consequently depends on socio-economic and political relations (Kjekstad, 2007), most challenges for implementing LS-DRR measures are to be sought within a political economy perspective. Nonetheless, the view that science is neutral and only decision-makers are responsible for implementation remains dominant (Cannon, 2008). This is illustrated by the fact that many publications still use outdated concepts like 'natural' disasters, although it is internationally acknowledged that disasters are socially constructed, i.e. their causes are both bio-physical as well as social, economic and political (Wisner et al., 2004).

The different challenges for implementing LS-DRR measures that were identified in this literature review are classified in political, scientific, social, economic, related to disaster risk management and geographic bottlenecks (Table 6). The main bottlenecks are scientific (30%) and political (29%) in nature, corresponding to the first two priorities of the Sendai Framework, i.e. (1) understanding disaster risk and (2) strengthening disaster risk governance to manage disaster risk (UNISDR, 2015). In the following sections, these two main categories of bottlenecks are described in detail with examples from our literature review. The other categories can be found in Table 6.

***3.1 Understanding landslide risk.*** Much progress is made in understanding LS risk in tropical LS-prone countries, i.e. through LS risk assessment, however gaps remain in scientific knowledge. The fact that scientific bottlenecks are cited as the most important in the

**Table 6.** Number of publications on landslide risk reduction (# pubs LS-DRR) in Scopus for the period January 2005 to January 2015 and number of countries (# countries) citing bottlenecks for implementing landslide risk reduction measures ( $n$  total = 109) by tropical region and in total.

Category	Bottlenecks	# pubs LS-DRR				Total (%)	# countries
		Africa	Asia-Pacific	Latin America	Total		
Scientific		1	15	17	33	30	20
	Lack of (reliable) data on hydro-meteorology and landslide inventory	1	8	10	19	17	10
	Lack of risk communication	0	4	1	5	5	2
	Lack of scientific knowledge and scientific capacities	0	1	3	4	3	4
	Lack of proper risk/hazard assessment to suggest DRR measures	0	1	2	3	3	3
	Poor translation of landslide hazard mapping into DRR measures	0	1	1	2	2	2
Political		1	15	16	32	29	25
	Lack of stable environment	0	2	9	11	10	10
	Lack of institutionalisation of DRR	0	8	2	10	9	6
	Focus on post-disaster emergency actions instead of pre-disasters measures	1	2	3	6	6	5
	Lack of community participation	0	2	0	2	2	2
	Lack of law enforcement	0	1	0	1	1	1
	Lack of enabling policies	0	0	1	1	1	1
	Lack of institutional capacity	0	0	1	1	1	1
Social		1	10	4	15	14	11
	Underestimation or denial of landslide risk	0	6	2	8	7	5
	Lack of community acceptance and ownership	0	3	2	5	5	4
	DRR measures in conflict with short-term livelihood	1	0	0	1	1	1
	Poor awareness on underlying causes and triggering factors of landslides	0	1	0	1	1	1
Economic		1	8	4	13	12	8
	Lack of financial resources of government and groups at risk	1	8	4	13	12	8
Disaster risk management		0	4	7	11	10	10
	Lack of coordination/cooperation between agencies	0	3	1	4	4	4
	Scattered and local efforts by NGOs and by governments	0	1	2	3	3	3
	Lack of multi-hazard approach instead of single-hazard approach	0	0	2	2	2	2
	No standardisation of data compilation and DRM procedures	0	0	2	2	2	1
Geographic		2	2	1	5	5	5
	Inaccessibility of areas at risk of landslides	2	2	1	5	5	5
Total # pubs		6	54	49	109	100	

literature (Table 6) can partly be attributed to the dominance of natural sciences in the literature on LS-DRR.

The most important scientific impediment is the lack of LS inventories and reliable data on hydro-meteorology (19 publications). LS are often underreported (Wamsler, 2007) or even missing in many LS-prone tropical countries (Nadim and Lacasse, 2008; Petley, 2012) because they are low-intensity, high-frequency hazards and also often considered inseparable from other natural hazards, such as extreme precipitation, earthquakes and floods (e.g. Jacobs et al., 2016). For instance, in Malaysia LS are only reported when casualties occur or infrastructural damage is severe (Althuwaynee et al., 2014). Consequently, most risk assessments tend to focus on susceptibility mapping instead of the more detailed hazard and risk mapping, while it is especially the risk aspect that is crucial for providing improved mitigation (Nadim and Lacasse, 2008). The translation of susceptibility or hazard assessment into risk, requires not only the identification of elements at risk, but also the estimation of loss functions for expected impacts (Vranken et al., 2015). Realistic LS risk assessments remain a challenge that is not only restricted to the Global South, which indicates a need for the development of adequate methods (Corominas and Mavrouli, 2011). The Sendai Framework, however, points out the need for a persistent knowledge transfer of current disaster risk understandings from North to South (UNISDR, 2015).

The challenge for LS-DRR is thus not only a lack of available appropriate mitigation measures (Corominas et al., 2013) but also the poor translation of LS risk assessment into actual slope management (e.g. DeGraff, 2012; Majid et al., 2007; UNISDR, 2014). This is also illustrated by the fact that there has been a minimal uptake of LS hazard maps and vulnerability assessments into policy actions by governments, as argued by Anderson et al. (2014)

based on evidence from Caribbean countries. There is a lack of communicating LS risk from the academic world to decision-makers as well as from decision-makers to groups at risk due to difficulties in translating the scientific content of the models and their associated uncertainties into more generalised, simplified and practically applicable formats (e.g. Jaiswal and van Westen, 2013; Leroi, 2005). Risk communication can be seen as a two-way interactive tool for sharing risk information among government officials, researchers and communities-at-risk (Shaw et al., 2009). It seems that, currently, sharing this risk information is not interactive nor done in a systematic manner. In many cases risk reduction measures are not delivered on the ground but rather delivered as secondary output such as maps, policies and (building) codes (e.g. in St Lucia: Mycoo, 2011). This lack of delivery is partly attributed to the fact that cost-benefit analyses and inclusive multi-criteria analyses are largely absent in scientific literature.

**3.2 Strengthening landslide risk governance.** The most restricting political condition is the lack of a stable environment for scientific development, land use planning and ensuring the continuity of risk reduction activities (11 publications; Table 6). This might be attributed to several reasons, such as the high rates of staff turnover, changes to institutional mandates, the short lives of some geosciences institutions and the fluctuating levels of foreign-exchange rates in many LS-prone tropical countries (e.g. Devoli et al., 2007; Jaramillo, 2008; Künzler et al., 2012). Due to a lack of long-term commitment by the government, low-budget but relatively long-term and time-consuming activities are neglected (DFID, 2004; Gue et al., 2009). Especially the lack of secure land tenure rights is considered as a major driver for the misuse of lands (Hofer, 2013).

Another challenge is the lack of institutionalisation of LS-DRR, i.e. the integration of LS-



DRR into the national institutional framework (eight publications). Although this institutionalisation was one of the main priorities that the HFA strove for, the actual implementation remains superficial. Countries with a national slope stability plan as part of their disaster risk management plan are still scarce. We found evidence of available plans only in Costa Rica (Andreas and Allan, 2007), Malaysia (Motoyama and Abdullah, 2013) and Sri Lanka (Bandara and Weerasinghe, 2013). While recently countries are starting to incorporate LS-DRR into their institutional frameworks (Gue et al., 2009), actual implementation remains low due to limited law enforcement (e.g. Ahammad, 2011), poor inclusion of local stakeholders (El-Masri and Tipple, 2002; Santi et al., 2011) and few policy actions that are based on site-specific scientific knowledge.

Setting political priorities on LS-DRR remains challenging in many tropical LS-prone countries. Nationally a focus remains on post-LS emergency actions (six publications). In practice DRR is only considered after LS events happen and enough media attention is given (e.g. Hori and Shaw, 2014). A global review on the status of institutional and legislative systems for LS mitigation in 2009 confirms this focus on response and recovery (Gue et al., 2009). This is explained by the fact that decision-makers hesitate to invest in projects with unobservable benefits combined with the absence of cost-effectiveness studies (Anderson et al., 2014). Moreover, LS are very localised and often affect marginalised populations, thus attracting considerably less political attention compared to large-scale events such as floods or drought.

#### 4 Methodological limitations

This literature review is affected by some limitations. A bias in the dataset exists because only peer-reviewed publications with English

abstracts have been consulted. Many LS-DRR efforts are published in the national language of the country affected or not published in scientific journals, but only as reports by governments, NGOs and private sector actors, or not published at all, such as indigenous knowledge or ‘silent evidence’ (e.g. Taleb, 2007). Other LS studies (Gokceoglu and Sezer, 2009; Gutiérrez et al., 2010; Sepúlveda and Petley, 2015) have, however, used similar methods as this literature review. Furthermore, several observations and trends are based on small numbers of publications, so the reported statistics should be considered indicative.

To investigate this bias, an additional survey of the grey literature for Uganda was made to check for inconsistencies. Including grey literature shows that looking at peer-reviewed scientific literature tends to neglect the implemented governance and awareness components of LS-DRR in the case of Uganda (Figure 8). This Ugandan case-study thus illustrates that recommendations made by authors of peer-reviewed publications do not necessarily align with those made by governments or civil society actors. The clear preference for implementing LS risk assessment is, however, visible in both reviews.

## IV Conclusions and recommendations

The literature on landslides (LS) and landslide disaster risk reduction (LS-DRR) is rapidly increasing worldwide (Gutiérrez et al., 2010; Wu et al., 2015). Our review shows that:

- the factors that influence the number of publications on LS and LS-DRR per country are the absolute physical exposure of people to LS ( $\rho = 0.77; 0.73$ ), the population ( $\rho = 0.55; 0.61$ ) and – to a lesser extent – the HDI of a country ( $\rho = 0.35; 0.32$ );
- the ratio of publications on LS-DRR versus publications on LS for LS-prone

tropical countries for the period 2005–2015 does not differ much between these countries (0.28);

- the vast majority (0.64) of all publications on LS-DRR in the tropics was published in journals or proceedings relating to ‘natural sciences’.

Our review further clarifies the main recommended and implemented LS-DRR measures to date based on the compiled classifications of Twigg (2007) and Vaciago (2013; Table 4). More specifically, it shows that:

- a significant fraction (0.30) of all potential LS hazard reduction measures (as classified by the SafeLand project) are neither recommended nor implemented for the tropics;
- the most recommended LS-DRR component (expressed as a fraction of all measures cited) for the tropics is ‘risk management and vulnerability reduction’ (0.38), while the most implemented component is ‘risk assessment’ (0.57);
- the ratio of implemented versus recommended LS-DRR measures in the tropics is rather low for most LS-DRR components (‘risk management and vulnerability reduction’: 0.25; ‘preparedness and response’: 0.27; ‘governance’: 0.36; ‘knowledge and education’: 0.47), except for ‘risk assessment’ (3.01);
- the most cited bottlenecks for implementing LS-DRR measures (expressed as a fraction of all bottlenecks cited) are scientific (0.30) and political (0.29).

Based on this study, several research needs for LS-DRR can be distilled. Overall, this review shows that a lot of research has focused on understanding landslide susceptibility and hazards in relation to the bio-physical factors that control them. However, quantitative assessments of the impacts of LS are much

rarer. Also, scientific assessments of the effectiveness of implemented DRR measures are largely lacking in the current scientific literature. Nonetheless, such information is crucial to support cost-benefit analyses and research on how to effectively translate risk assessment into risk reduction measures. This will require multi-criteria analyses identifying the most effective LS-DRR measures as a function of the spatial scale, the type of LS, the (potential) impact, the underlying root causes and bottlenecks, which are currently lacking at national and lower levels.

Moreover, it appears that the responsibility of scientists cannot end at the identification and characterisation of LS hazard and risk, or the recommendation of generic DRR measures. Effectively reducing LS risks will not only require better scientific insights, but also efforts to communicate and transfer scientific research results to policy makers and the population at risk. Involving stakeholders at all stages of the scientific research, i.e. from problem identification to delivery of the most practical results, is crucial to promote ownership and to ensure more site-specific and effective efforts. As landslide research currently remains mainly driven by earth scientists, this will require initiatives in developing trans-disciplinary approaches that are able to go beyond the analysis of the physical drivers of LS, but integrate the social, political, cultural and economic dimensions of DRR in order to identify and characterise the effectiveness of specific DRR measures (Cutter et al., 2015). Hence, earth scientists should actively seek interactions with experts in social sciences and grass-root organisations in order to bridge the gap between the improved understanding of landslide hazard and the effective reduction of landslide risk.

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