

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

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Keywords:	mass movements, disaster risk reduction, resilience, mitigation measures, Global South, tropical countries, research needs
Abstract:	<p>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 at (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.</p> <p>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 using a scheme of risk reduction measures that combines classifications of the Hyogo Framework for Action and the SafeLand project.</p> <p>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 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.</p>

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32 13 landslide-prone tropical countries was made, based on an extensive review of scientific
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34 14 literature (382 publications). The documented measures are analysed using a scheme of risk
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11 29 measures are scientific (0.30) and political (0.29) in nature.
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14 30 Keywords

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25 34 1. Introduction

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28 35 Landslides (LS) are defined as 'the movement of a mass of rock, debris or earth down a slope'
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30 36 (Cruden, 1991:27). They present a serious problem in many regions worldwide, claiming
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32 37 thousands of deaths per year (Petley, 2012). Especially in the tropics, many regions are
33
34 38 strongly affected by LS due to high precipitation and weathering rates, particularly in zones
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36 39 with steep topography and tectonic activity (Kirschbaum et al., 2015). Moreover, LS risk in
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38 40 the tropics is expected to increase in the near future as a response to increasing demographic
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40 41 pressure, deforestation and land use changes (Kjekstad, 2007) as well to climate change
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42 42 (Gariano and Guzzetti, 2016). In addition, most fatalities due to LS occur in the Global South
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44 43 countries that are predominantly located within the tropics (Kirschbaum et al., 2015; Petley,
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46 44 2012). Furthermore, the impact of LS on the population can be very high in tropical
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48 45 developing countries due to their high economic, social, political and cultural vulnerability
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50 46 (Alcántara-Ayala, 2002).
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3 47 The recent Sendai Framework for Disaster Risk Reduction (DRR) has renewed the
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5 48 international focus on reducing risk of disasters (UNISDR, 2015). Investing in DRR was
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7 49 identified as one of the key priorities. Disaster 'risk' is defined as 'the potential disaster
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9 50 losses, in lives, health status, livelihoods, assets and services, which could occur to a
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11 51 particular community or a society over some specified future time period' (UNISDR, 2009:9),
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13 52 while 'hazard' refers to the natural event itself that may affect different places singly or in
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15 53 combination at different times (Wisner et al., 2004). According to UNISDR (2009:10), DRR
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17 54 is 'the concept and practice of reducing disaster risks through systematic efforts to analyze
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19 55 and manage the causal factors of disasters, including through (i) reduced exposure to hazards;
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21 56 (ii) lessened vulnerability of people and property; (iii) wise management of land and the
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23 57 environment; and (iv) improved preparedness for adverse events'. Especially for low-
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25 58 intensity, high-frequency events like LS, DRR is considered the most cost-effective option to
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27 59 limit the negative impacts of disasters (Mechler, 2010).
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32 60 It is relevant to first analyze what is currently being recommended and implemented globally
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34 61 to support research and investment in DRR (UNISDR, 2015). A hazard for which such a
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36 62 review of risk reduction (or mitigation) measures is still lacking is LS. As the scientific
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38 63 literature on LS is rapidly increasing (Gutiérrez et al., 2010; Wu et al., 2015), it is important
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40 64 to maintain an overview, meaning that we understand which LS-DRR is being investigated
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42 65 and where, what explains observed differences between recommended and implemented
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44 66 measures and which potential pitfalls the implementation of such DRR is facing. Although
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46 67 such overview is certainly relevant to a wide audience, this is especially the case for earth
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48 68 scientists since most of the research on LS is currently conducted by this research community.
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50 69 A meta-analysis of recommended and implemented measures may certainly help in
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52 70 identifying the next steps to contribute to long-term LS-DRR.
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3 71 The overall objective of this review is therefore to gain more insights into the implementation
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5 72 of LS-DRR measures applied and recommended in tropical LS-prone countries, and the
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7 73 challenges at play. We focus on the tropics for two reasons. First, this research frames in the
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9 74 AfReSlide project (Kervyn et al., 2015), which tries to identify LS-DRR measures for tropical
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11 75 countries like Uganda and Cameroon. This study thus serves as a good starting point to
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13 76 understand LS-DRR in these two countries. Second, LS risk is expected to increase in tropical
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15 77 regions due to climate change, while many of these regions in Africa, South America and
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17 78 Asia are currently understudied (Gariano and Guzzetti, 2016). The projected increases in the
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19 79 intensity and frequency of extreme precipitation events in the tropics (IPCC, 2014) and
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21 80 subsequently on increasing LS risk (Seneviratne et al., 2012) serve as a valid reason to target
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23 81 tropical LS-prone countries for our analysis. The specific objectives are: (i) to compile an
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25 82 overview of studies on LS and LS-DRR in tropical LS-prone countries, (ii) to explore the
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27 83 factors controlling the number of scientific studies conducted on LS and LS-DRR per country,
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29 84 (iii) to review the various LS-DRR measures recommended and implemented, and (iv) to
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31 85 identify the bottlenecks for implementing these measures.
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87 2. Materials and methods

88 2.1 Selection of study area and country-specific data

89 In this study, we only considered countries for which (1) at least 50% of their land area lies
90 between the tropical circles and (2) if at least one inhabitant per year was exposed to either
91 rainfall- or earthquake-triggered LS per year, according to the Global Risk Data collected by
92 the Norwegian Geotechnical Institute (NGI) for the Global Assessment Report on DRR
93 (Giuliani and Peduzzi, 2011). This Global Risk Data is to our knowledge the most complete

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3 94 and consistent global dataset. It expresses the absolute physical exposure to LS as the
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5 95 expected average annual population exposed (# inhabitants/year) and is based on the
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7 96 modelling of LS susceptibility and population density (NGI, 2013). Ninety-nine out of the
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10 97 138 tropical countries met this second criterion and were considered for our review on
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12 98 recommended and implemented DRR measures for LS (Table 1). Evidently, the Global Risk
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14 99 Data used to identify the LS-prone countries is subject to uncertainty. This uncertainty,
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16 100 combined with the relatively coarse spatial resolution of the data, may induce erroneous
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18 101 inclusions or exclusions in our list of tropical LS-prone countries. Especially some small
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20 102 island states are not LS-prone according to this database, while this is not necessarily the case
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22 103 (Table 1). E.g. the Bahamas (Buchan, 2000), the Seychelles (Payet, 2005), and St. Vincent
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24 104 and the Grenadines (Anderson et al., 2010). Therefore, this list should be interpreted with
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26 105 caution. To investigate the potential extension of these errors, we also checked for each not
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28 106 landslide-prone country whether articles on LS-DRR were published for that country (using
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30 107 the same methodology and criteria described in section 2.2). This was the case for 9 countries
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32 108 (Table 1). However, given their small area, limited population and publication count, the
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34 109 impact of these wrongfully assigned countries on our analyses is likely to be very limited. On
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36 110 the other hand, the Global Risk Data (NGI, 2013) provided an independent and objective
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38 111 criterion of countries to focus on. This helped avoiding that our literature review was biased
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40 112 towards our prior knowledge of available literature. We therefore decided not to further
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42 113 correct or adapt our list of LS-prone countries and to focus our review on the tropical
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44 114 countries that were indicated as LS-prone based on the Global Risk Data (NGI, 2013).

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3 117 In order to identify the factors controlling the application rate of LS-DRR measures, data on
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5 118 the Human Development Index (HDI) and the physical exposure to LS were collected for
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7 119 each tropical LS-prone country (n = 99). The HDIs of 2013 were collected from the Human
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9 120 Development report of 2014 (Malik et al., 2014). For 14 out of the 99 countries, data on HDI
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11 121 were not available. Most of these 14 countries are island states. The physical exposure of
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13 122 people to LS, i.e. the overlay of population density with LS susceptibility, was collected from
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15 123 the Global Risk Data of the Norwegian Geotechnical Institute (NGI, 2013; Fig. 1). The LS
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17 124 susceptibility depends on the slope gradient, lithology (or geology), soil moisture, vegetation
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19 125 cover, precipitation and seismicity (NGI, 2013). The population data were retrieved from the
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21 126 UN Population Division and cover data of 2010 which was also used for the physical
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23 127 exposure (NGI, 2013). In order to obtain country-specific data, the physical exposure values
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25 128 for both precipitation- and earthquake-triggered LS were summed up for every pixel lying
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27 129 within the country's boundaries.
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38 132 2.2 Compilation of scientific literature 39

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41 133 Scopus[®] (Elsevier B.V., 2015) was chosen as the search engine to select articles for the
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43 134 detailed review on recommended and implemented LS-DRR measures. Initially, literature
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45 135 was searched using Web of Science[™] (WoS; Thomson Reuters, 2015), Google Scholar
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47 136 (Google, 2015) as well as Scopus because these search engines cover most published
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49 137 scientific literature (Falagas et al., 2007). Scopus however yielded the highest number of
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51 138 countries with publications and includes more social sciences oriented publications besides
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53 139 natural sciences which is deemed crucial for this research (Table 2). Furthermore, Scopus
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3 140 produces more citation counts than WoS (Bergman, 2012; Falagas et al., 2007) and it has
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5 141 been shown to result in less inconsistencies regarding content verification compared to WoS
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7 142 and Google Scholar (Adriaanse and Rensleigh, 2013).
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10 143 An inventory of peer-reviewed articles on LS and LS-DRR, published between January 2005
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12 144 and January 2015, was thus made using Scopus. The keywords and Boolean search criteria
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14 145 described below were applied to the 'title', 'abstract' and 'keywords' simultaneously. In order
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16 146 to analyse the literature on LS-DRR, we first searched for publications on LS in general and
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18 147 then specifically publications on LS-DRR. For the LS literature, we used the following
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20 148 keywords and Boolean search criteria: <country name> AND (landslide* OR 'mass
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22 149 movement' OR 'mass wasting'). For the LS-DRR literature, we used the same keywords and
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24 150 Boolean search criteria but added the terms 'prevention', 'management', 'mitigation', 'risk
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26 151 reduction' or 'remediation' in order to narrow down to DRR. Only peer-reviewed publications
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28 152 with English abstracts have been taken into account. An overview of the compiled literature is
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30 153 given in Table 2. Noteworthy is that 25% of the 536 publications concerned India. After
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32 154 detailed investigations, 154 out of the 536 LS-DRR publications were excluded because they
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34 155 were irrelevant for this research (e.g. articles on submarine LS). As a comparison, not tropical
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36 156 LS-prone countries like Italy and the USA respectively yield 1,529 and 208 publications on
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38 157 LS, and 294 and 37 publications on LS-DRR, using the same keywords and Boolean search.
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49 160 Not all the research on LS-DRR in LS-prone tropical countries was published in peer-
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51 161 reviewed articles. To evaluate to what extent our review might be biased by the fact that only
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53 162 scientific peer-reviewed literature was considered, we conducted a much broader search,
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3 163 including 'grey literature', for Uganda. This country was chosen as a case-study due to an in-
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5 164 depth expertise by the authors and easy access to internal documents from national experts.
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7 165 Such access could not be obtained for the other countries considered. The grey literature
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9 166 considered includes reports of government institutions, NGOs, dissertations of national and
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11 167 foreign master students, retrieved through personal secondary data collection in Uganda and
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13 168 targeted search in Google. In total 16 documents on LS-DRR were selected for Uganda in
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15 169 addition to the three peer-reviewed publications found in Scopus. This grey literature is by no
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17 170 means exhaustive but representative judging from expert knowledge.
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24 172 2.3 Factors explaining the number of publications on landslides and landslide risk reduction

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27 173 The initial search in Scopus resulted in 1928 LS publications and 536 LS-DRR publications
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29 174 (Table 2). Correlations between the number of publications and potential controlling factors,
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31 175 like HDI, physical exposure to LS and population numbers were searched for using the
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33 176 Spearman rank correlation (ρ) as this method is not sensitive to outliers (Heinisch, 1962). In
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35 177 addition, we calculated Partial Spearman rank correlations (partial ρ), which measures the
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37 178 degree of association between two considered variables, with the effect of one or more
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39 179 controlling variables removed (Heinisch, 1962). For these analyses, only the 85 countries
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41 180 having an available HDI were used.
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49 182 2.4 Classifications

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3 184 To examine the LS-DRR research output in the tropics, the compiled publications on LS-DRR
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5 185 were classified in terms of spatial scale of analysis, authors' country of origin, authors'
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7 186 organisation, and research discipline. For the spatial scale of analysis, the compiled
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9 187 publications were classified into six categories: local (e.g. cities, villages, roads and
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11 188 catchments), provincial (e.g. districts and states), national, regional and global (e.g. global
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13 189 scale highlighting a specific country as an example). For the authors' country of origin, the
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15 190 four categories are: national, foreign, mixed national and foreign, and unknown. For the
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17 191 authors' organisation, the six categories are: university, government, non-governmental
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19 192 organisation (NGO), private sector, multiple organisations and unknown. For the research
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21 193 discipline, the journals and proceedings in which the publications were published were
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23 194 divided into four categories: natural science, social science, interdisciplinary and unknown.

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28 195 To classify the LS-DRR measures, we used the general DRR classification suggested by
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30 196 Twigg (2007). This classification consists of five components: (i) risk management and
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32 197 vulnerability reduction, (ii) governance, (iii) knowledge and education, (iv) preparedness and
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34 198 response, and (v) risk assessment. 'Risk management and vulnerability reduction' contain all
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36 199 measures related to reducing the occurrence of LS hazards, the vulnerability to LS and the
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38 200 exposure to LS. 'Governance' relates to institutional frameworks and policies on LS-DRR.
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40 201 'Knowledge and education' consist of all measures related to awareness raising on LS.
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42 202 'Preparedness and response' comprise all measures dealing with early warning and
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44 203 emergency response. 'Risk assessment' includes all aspects of understanding LS risk. These
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46 204 five components can then be further classified into specific risk reduction measures. The
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48 205 classification of LS-DRR has been the subject of much debate (Nadim and Lacasse, 2008).
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50 206 Here we used the classification of the SafeLand project to further divide the component of
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52 207 'risk management and vulnerability reduction' in subcategories (see section 3.2), since this
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3 208 was the most recent classification and since it was based on a comprehensive literature review
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5 209 (Vaciago, 2013). For a detailed description of specific LS-DRR measures we refer to Twigg
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7 210 (2007) and Vaciago (2013).
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10 211 Using this classification, the implemented and recommended LS-DRR measures in LS-prone
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12 212 tropical countries were identified by screening the abstract and conclusions of the 382
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14 213 collected publications on LS-DRR in Scopus for the period Jan. 2005 to Jan. 2015. With
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16 214 implemented LS-DRR measures, we understand specific actions and techniques that are
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18 215 mentioned in the article (not necessarily with detailed explanation) as currently being
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20 216 developed or operational. Similarly, with recommended measures we mean specific actions
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22 217 and techniques that are suggested as recommendations (not necessarily with detailed
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24 218 explanation) but not yet developed or operational in the country.
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28 219 Finally, the bottlenecks for implementing LS-DRR measures have been identified by
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30 220 screening the abstract and conclusions of the 382 publications. After identification, these
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32 221 bottlenecks were classified into six sections based on our own judgement: i.e. scientific,
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34 222 political, social, economic, disaster risk management related and geographic bottlenecks. All
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36 223 categories are however not mutually exclusive.
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41 42 43 225 3. Results and discussion

44 45 46 226 3.1 Analysis of the number and nature of publications

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3 229 Several factors influence the number of publications on LS per country (#pubs LS/co; Table 3
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5 230 and Fig. 2).

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8 231 [Insert Fig. 2.]

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13 233 The #pubs LS/co best correlates with the absolute physical exposure of people to LS per
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15 234 country ($\rho = 0.77$, $p < 0.001$; Table 3), which suggests that countries with a larger exposed
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17 235 population (e.g. Philippines in comparison with Guatemala) are generally more concerned
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19 236 about LS (Fig. 2a). This is, of course, assuming that the number of publications reflects the
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21 237 level of concern. High risk perception does however not necessarily result into more
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23 238 preparedness as indicated by Wachinger et al. (2013). The partial correlation between the
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25 239 absolute physical exposure and the #pubs LS/co remains significant after controlling for the
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27 240 effect of the other controlling variables, i.e. HDI (partial $\rho = 0.77$, $p < 0.001$) and population
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29 241 (partial $\rho = 0.68$, $p < 0.001$). The countries with the relatively lowest LS publication count per
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31 242 exposed citizen are Indonesia, Philippines, Guatemala, Costa Rica, Ethiopia, Colombia, India
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33 243 and Myanmar, while Malaysia and Brazil have the highest publication count – absolute
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35 244 physical exposure ratio (Fig 2a). Noteworthy is that the #pubs LS/co is also correlated with
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37 245 the relative physical exposure, i.e. the people exposed to LS per country divided by the total
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39 246 population per country ($\rho = 0.49$, $p < 0.001$; Table 3).

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48 249 The #pubs LS/co is also correlated with population ($\rho = 0.55$, $p < 0.001$, Fig. 2b; Table 3).

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51 250 The Spearman rank is smaller for the correlation with population than with the absolute

251 physical exposure per country, despite the lower coefficient of determination. This correlation
252 remains significant after removing the effect of the other controlling variables, i.e. absolute
253 physical exposure of people to LS (partial $\rho = 0.28$, $p < 0.01$) and HDI (partial $\rho = 0.67$, $p <$
254 0.001).

255 The third most important determining factor is the HDI of a country ($\rho = 0.35$, $p < 0.001$; Fig.
256 2c; Table 3). This correlation remains significant after removing the other controlling
257 variables, i.e. the absolute physical exposure of people to LS (partial $\rho = 0.34$, $p < 0.01$) and
258 population per country (partial $\rho = 0.55$, $p < 0.001$). This correlation suggests that countries
259 with a high HDI have more resources to support scientific research, including on LS. This is
260 in line with the correlation made by Petley (2012) indicating that globally, countries with the
261 highest #pubs LS/co have generally lower numbers of fatalities. However, this correlation is
262 relatively weak and clearly less significant than the absolute physical exposure to LS.

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

271 3.1.2 Nature of publications on landslide risk reduction

272 On average, there are 20 publications on LS per country and five publications on LS-DRR
273 (Table 2). Figure 3 shows the number of publications on LS and LS-DRR per tropical LS-

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3 274 prone country for the period Jan. 2005 - Jan. 2015. Overall, these maps indicate that
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5 275 especially larger countries in Asia and South America (e.g. India and Brazil) have a high
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7 276 number of publications on LS and LS-DRR, while most African countries clearly have less
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9 277 peer-reviewed literature on these subjects.

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18 280 The LS-DRR literature from Scopus is described in detail in the following paragraphs. In
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20 281 terms of spatial scale, the largest number of the 382 consulted publications are local (176
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22 282 pubs), while articles focusing on a provincial scale form the second largest group (88 pubs;
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24 283 Fig. 4). The third largest group consists of studies for which the spatial scale could not be
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26 284 clearly identified (51 pubs).

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36 287 Overall, up to 52% of all the 382 publications involve scientists from the country of interest.
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38 288 This percentage is clearly smaller for Africa and Latin America than for Asia and the Pacific
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40 289 (Fig. 5). Interestingly, a relatively large percentage of the publications involve only foreign
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42 290 institutions (24%). In African and Latin American countries, publications conducted by only
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44 291 foreign institutions form even the largest group (42% and 36% respectively). Knowing that
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46 292 only 6% of the compiled articles concerns LS in Africa, this indicates that the number of
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48 293 African scientists publishing on LS is very small.

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51 294 [Insert Fig. 5.]
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3 296 Universities employ the largest percentage of authors (41%). In Africa, however, a fairly large
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5 297 percentage is connected to a NGO (25%), while collaborative research between different
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7 298 types of actors is also common (38%; Fig. 6).
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16 301 The literature on LS-DRR is dominated by natural sciences, as 65% of the articles was
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18 302 published in a 'natural science' journal or proceedings volume, 19% in an 'interdisciplinary',
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20 303 only 2% in a 'social science', and 14% in a journal or proceedings volume of unknown
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26 306 3.2 Overview of landslide risk reduction measures

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31 307 Of all LS-DRR measures, 'LS risk assessment' is by far the most implemented DRR
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33 308 component (57%), while 'risk management and vulnerability reduction' is the most
34
35 309 recommended DRR component (38%; Fig. 7). 'LS risk assessment' is the most implemented
36
37 310 component in all regions, but receives relatively more attention in Africa (72%) which might
38
39 311 be attributed to the fact that landslide hazard research is still emerging on this continent and
40
41 312 that governance remains a challenge for the implementation of other DRR actions (UNISDR,
42
43 313 2012). While 'LS risk management and vulnerability reduction' is the most recommended
44
45 314 component in all tropical regions, it receives somewhat less attention in Asia-Pacific (27%) as
46
47 315 compared to Africa (40%) and Latin America (42%). Generally, implemented and
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49 316 recommended measures vary relatively little between different regions.
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54 317 [Insert Fig. 7.]
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7 319 Overall, 575 LS-DRR measures were cited as being implemented in 304 articles, while 906
8 320 measures were recommended in 279 articles (Table 4). In the following sections, each LS-
9 321 DRR component is described in detail, first, by stating the most recommended measures,
10 322 second, the most implemented measures and, third, by explaining their
11 323 implementation/recommendation ratio.
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17 324 [Insert Table 4.]
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26 326 Noteworthy is that the main focus of landslide research remains on ‘hazard’ assessment. This
27 327 focus might be explained by the fact that disaster research is rooted in the natural sciences
28 328 (Watts, 1983). Our review also indicates that implemented LS-DRR measures are dominantly
29 329 focusing on the collection of ‘hazard’ instead of ‘vulnerability’ data. Of the 255 publications
30 330 citing the implementation of ‘collection of hazard/risk data and assessment’ (Table 4), 236
31 331 publications refer to the collection of ‘hazard’ data, while only 19 cite the collection of ‘risk’
32 332 data. This focus on understanding hazards in disaster research is however gradually shifting
33 333 towards understanding vulnerability and loss of resilience to disasters (Manyena et al., 2013).
34 334 Our review shows that this shift is indeed increasingly being recommended but not yet
35 335 reported as implemented. Similarly, most publications focusing on the combination of both
36 336 hazard and vulnerability, i.e. risk, are relatively new (69% of these studies were published in
37 337 2010 or later).
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50 338 3.2.1 Risk management and vulnerability reduction
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3 339 'Risk management and vulnerability reduction' is the most recommended component (38%,
4
5 340 342 pubs) while being amongst the least implemented component (15%, 84 pubs; Table 4;
6
7 341 Fig. 7). This component faces the least progress of all DRR components for all hazards
8
9 342 globally (UNISDR, 2013). Our review suggests the same for LS in tropical LS-prone
10
11 343 countries despite being highly recommended. The fact that LS risk management and
12
13 344 vulnerability reduction is highly recommended might be because it involves LS-specific
14
15 345 actions whereas others are valid for all hazards.

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19 346 For the 'risk management and vulnerability reduction' component, a list of specific actions for
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21 347 each category of our combined classification is provided in Table 5, based on the SafeLand
22
23 348 project that presents the most recent classification and is based on a comprehensive literature
24
25 349 review (Vaciago, 2013). Table 5 illustrates that many measures listed by the SafeLand project
26
27 350 are neither implemented nor recommended, e.g. expensive measures like drainage tunnels and
28
29 351 deep mixing with lime and/or cement. This indicates that, although complete, this
30
31 352 classification is too comprehensive for LS-prone tropical countries.

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34
35 353 Risk zoning for land use planning is mostly recommended and implemented in the literature
36
37 354 for the tropics (117 and 15 pubs, respectively) followed by bio-engineering techniques (32
38
39 355 and 6 pubs, respectively; Table 5). Noteworthy as well is the recommendation and
40
41 356 implementation of the modification of the surface water regime (39 and 15 pubs,
42
43 357 respectively).

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46
47 358 'LS risk management and vulnerability reduction' has a relative low
48
49 359 implementation/recommendation ratio, i.e. 0.25 (Table 4). Similarly, Anderson et al. (2014)
50
51 360 state that the implementation of LS hazard reduction measures, also known as remedial or
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1
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3 361 slope stabilisation measures, is limited in many tropical regions mainly because of the
4
5 362 perceived high costs.
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8 363 [Insert Table 5.]
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12 365 3.2.2 Governance

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16 366 Governance is cited as the second most recommended LS-DRR component (20%, 184 pubs;
17
18 367 Table 4; Fig. 7). Likewise, it is the second most implemented component (11%, 66 pubs).
19
20 368 This strong attention for governance might be explained by the strong emphasis of the Hyogo
21
22 369 Framework for Action (HFA) on nations as prime actors for setting up DRR measures
23
24 370 (Twigg, 2007). Since the ratification of the HFA in 2005, disaster governance is put forward
25
26 371 as a key priority (UNISDR, 2015).
27
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29
30 372 The most commonly recommended and implemented governance actions are the
31
32 373 improvement of institutional mechanisms, capacities and structures and the allocation of
33
34 374 responsibilities (63 and 24 pubs, respectively; Table 4). The latter includes improving
35
36 375 coordination and communication in LS risk management and improving capacities at all
37
38 376 policy levels. These capacities vary largely between different tropical countries, according to
39
40 377 the level of decentralisation, the availability of resources and the political-administrative
41
42 378 structure (Maskrey, 2011).
43
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45
46 379 The ratio of implemented and recommended measures is, with an average value of 0.36,
47
48 380 rather low (Table 4). The measures with a clearly higher ratio are the integration of LS-DRR
49
50 381 with emergency response and recovery (1.00) and creating partnerships (0.75). Partnerships
51
52 382 between countries and within countries can be between the government and other
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3 383 stakeholders such as NGOs, the private sector and research institutes. Especially since the
4
5 384 HFA in 2005 and the first World Landslide Forum (WLF) in 2008 several international
6
7 385 partnerships have been established, e.g. regional networks of the International Consortium on
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9 386 LS in Latin America (Alcántara-Ayala et al., 2014), Asia (Billedo et al., 2013) and to a lesser
10
11 387 extent in Africa (e.g. Igwe, 2013). Other examples are the Multi-national Andean Project in
12
13 388 seven Latin American countries (Jaramillo, 2008), the Disaster Research Nexus for
14
15 389 collaborative research in Malaysia (Koh et al., 2012) and the Integrated Disaster Risk
16
17 390 Management Plans for 12 provinces within Vietnam (Long et al., 2010). The measure with a
18
19 391 relatively low implementation ratio is the integration of DRR with development policies and
20
21 392 planning (0.10). This low rate is in line with the call of the Sendai Framework for a common
22
23 393 ‘sustainable development’ and DRR agenda (UNISDR, 2015).

24 25 26 27 28 394 3.2.3 Knowledge and education

29
30 395 Knowledge and education is amongst the least recommended (15%, 133 pubs) and least
31
32 396 implemented LS-DRR components (11%, 62 pubs; Table 4; Fig. 7). Nevertheless, literature
33
34 397 suggests that it serves as a prerequisite for the implementation of any other measure (Wamsler
35
36 398 et al., 2012).

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39
40 399 The main recommendations for this DRR component are public awareness in combination
41
42 400 with the improvement of knowledge and skills (62 pubs), information management and
43
44 401 sharing (35 pubs) and education and training (24 pubs; Table 4). For example in Guatemala,
45
46 402 awareness on how to detect early warning signs is recommended (Santi et al., 2011). Because
47
48 403 local people are the first actors after a LS occurs, their role in DRR cannot be underestimated
49
50 404 (Parkash, 2013). It is therefore recommended that especially local people should be targeted
51
52 405 in awareness campaigns related to LS-DRR (e.g. in Sri Lanka: Dias et al., 2013). Remarkably,

1
2
3 406 cultural and individual behaviour receive very limited attention altogether although perception
4
5 407 and cultural representation of risk have been reported to be essential in the implementation of
6
7 408 DRR (Cannon and IFRC, 2014).

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9
10 409 Knowledge and education has a moderate implementation/recommendation ratio, i.e. 0.47
11
12 410 (Table 4). Cultures, attitudes and motivation has a high ratio (1.50). This measure includes
13
14 411 studying motivations for adopting measures and using indigenous knowledge for DRR.
15
16 412 Information management and sharing has a relatively higher ratio (0.89) and includes the
17
18 413 development of web-based or GIS tools for data collection as well as the development of
19
20 414 guidelines for implementation of LS-DRR measures. Education and training also has a
21
22 415 relatively higher ratio (0.54). Examples are the inclusion of LS-DRR topics in the university
23
24 416 curricula and the training of officials on LS-DRR. A national education program on LS has
25
26 417 been introduced in Bangladesh (Ali et al., 2014), Colombia (Hermelin & Bedoya (2008),
27
28 418 India (Parkash, 2013), Malaysia (Abdullah, 2013; Motoyama and Abdullah, 2013), Sri Lanka
29
30 419 (Bandara and Weerasinghe, 2013) and in Vietnam (Long et al., 2010). A distinctly small
31
32 420 number of studies discuss the implementation of public awareness schemes and improvement
33
34 421 of knowledge and skills on LS mitigation, despite the fact that this action is highly
35
36 422 recommended (0.18) and the positive effects of such DRR actions (e.g. Shaw et al., 2009).
37
38 423 This could be partly attributed to the limited involvement of scientists in this type of actions
39
40 424 (Cutter et al., 2015).

41 425 3.2.4 Preparedness and response

42
43 426 Preparedness and response to LS events is amongst the least recommended components (15%,
44
45 427 139 pubs) while also being the least cited implemented DRR component (7%, 38 pubs; Table
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47 428 4; Fig. 7).

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3 429 The main recommended and implemented measures belonging to this DRR component are
4
5 430 recognising physical signs that LS might occur in the near future (e.g. development of tension
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7 431 cracks), warning and subsequent evacuation (74 and 36 pubs, respectively), and contingency
8
9 432 planning to a limited extent (14 and 1 pubs, respectively; Table 4). Examples of measures like
10
11 433 implementing contingency plans (Scolobig et al., 2014) and temporarily relocation
12
13 434 (Gorokhovich et al., 2013) are fairly isolated. No scientific publications could be found on the
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15 435 evaluation of LS emergency response and recovery, coordination, response resource and
16
17 436 infrastructures nor the involvement of volunteers.

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20
21 437 Preparedness and response measures have a relative low implementation/recommendation
22
23 438 ratio, i.e. 0.27 (Table 4). Only early warning systems (EWS) have a higher ratio (0.49). For an
24
25 439 overview of EWS in South East Asia we refer to Billedo et al. (2013) and to Larsen (2008) for
26
27 440 EWS in general. LS are predicted based on monitoring earthquakes and rainfall events
28
29 441 (Bandara et al., 2013) or applying LS prediction models, e.g. in Indonesia (Liao et al., 2011),
30
31 442 and through community-based reporting systems, e.g. in the Philippines (Marciano et al.,
32
33 443 2011). LS monitoring is often considered as an effective and even affordable measure for
34
35 444 DRR and has helped to reduce the number of fatalities in several countries during recent
36
37 445 years, e.g. in Sri Lanka (Bandara et al., 2013).

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41 446 Interestingly, risk insurance is not often recommended despite an internationally growing
42
43 447 interest for its general implementation (UNISDR, 2013). This lack is most probably due to the
44
45 448 fact that risk insurance is less profitable for low-intensity, high-frequency events like LS as
46
47 449 losses might be covered more effectively domestically (Mechler et al., 2010) and because of a
48
49 450 lack of formal insurance markets in many rural areas in the tropics. Nevertheless Anderson
50
51 451 and Holcombe (2013) argue that social funds, i.e. informal insurance based on social
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3 452 relations, play a major role in the tropics and increasingly focus on the vulnerability
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5 453 component of LS-DRR (e.g. Mertens et al., 2016).
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8 454 3.2.5 Risk assessment

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10 455 Risk assessment is the least recommended (12%, 86 pubs) but most implemented LS-DRR
11
12 456 component (57%, 262 pubs; Table 4; Fig. 7). This might be attributed to the fact that risk
13
14 457 assessment is considered the first step towards LS risk management (Crozier and Glade, 2005;
15
16 458 DeGraff, 2012), which can also be seen in our literature review from the fact that 53% of
17
18 459 recommended measures are made in case risk assessment was already implemented. The large
19
20 460 focus on scientific knowledge about LS cannot only be attributed to the fact that we restrict
21
22 461 this review to peer-reviewed scientific literature, as a comparison with literature including
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24 462 grey literature for Uganda shows that the preference for implementing LS risk assessment is
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26 463 visible in both reviews (Fig. 8).
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31 464 [Insert Fig. 8.]
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37 466 Within this DRR component, the most frequently reported LS risk assessment techniques are
38
39 467 the collection and analysis of LS susceptibility, hazard and risk data (59 pubs for
40
41 468 recommendation, 255 pubs for implementation) including LS susceptibility and hazard
42
43 469 mapping (124 pubs for implementation) and the compilation of LS inventories (61 pubs for
44
45 470 implementation; Table 4). LS susceptibility mapping involves the classification and spatial
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47 471 distribution of current and potential LS in a certain area, while LS hazard mapping adds an
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49 472 estimated frequency to the potential LS (Fell et al., 2008). LS risk mapping goes further by
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51 473 taking the outcomes of the hazard mapping and assessing the potential damage to persons,
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53 474 private property, and infrastructure (Fell et al., 2008). The fact that the latter is more
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3 475 complicated explains why LS risk mapping is less implemented than susceptibility and hazard
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5 476 mapping (16 versus 97 pubs). A systematic procedure for assessing LS risk at national scale is
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7 477 in most cases lacking (but not necessarily desirable), except for countries like Brazil (Soler et
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9 478 al., 2013), Cuba (Abella and Van Westen, 2007), India (van Westen et al., 2012), Malaysia
10
11 479 (Abdullah, 2013) and Vietnam (Long et al., 2010). Important to note here is that an exclusive
12
13 480 promotion of LS susceptibility maps for landslide risk zoning, without site-specific hazard
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15 481 assessments for diagnosis and design of landslide hazard reduction measures, might
16
17 482 potentially lead to a lack of effective LS mitigation on the ground (Anderson et al., 2014). For
18
19 483 an extensive review on current landslide susceptibility mapping methodologies we refer to the
20
21 484 LAMPRE project (Malamud et al., 2014).

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25 485 LS risk assessment has a high implementation/recommendation ratio, i.e. 3.01 (Table 4).
26
27 486 Especially scientific and technical capacities and innovation have a very high ratio (4.32).
28
29 487 Noteworthy is that the only scientific and technical innovation cited in literature is the
30
31 488 identification of rainfall thresholds that might trigger LS. Countries where rainfall thresholds
32
33 489 have been identified are: Ecuador (Ibadango et al., 2007), India (Bhusan et al., 2014), Jamaica
34
35 490 (Miller et al., 2009), Malaysia (Althuwaynee et al., 2014), Mexico (Antinao and Farfan, 2013)
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37 491 and Puerto Rico (Wieczorek and Leahy, 2008).

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43 44 493 3.3 Bottlenecks for implementation of LS-DRR measures

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47 494 Despite the increased literature on LS-DRR measures (Gutiérrez et al., 2010; Wu et al., 2015),
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49 495 we show that the implementation of measures and their scientific documentation remains
50
51 496 rather scarce in the tropics. Furthermore, the low implementation/recommended ratio of most
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53 497 LS-DRR components and difference between recommended and implemented measures

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3 498 suggest that implementing LS-DRR measures remains challenging in the tropics. As their
4
5 499 implementation involves different actors and consequently depends on socio-economic and
6
7 500 political relations (Kjekstad, 2007), most challenges for implementing LS-DRR measures are
8
9 501 to be sought within a political economy perspective. Nonetheless, the view that science is
10
11 502 neutral and only decision-makers are responsible for implementation remains dominant
12
13 503 (Cannon, 2008). This is illustrated by the fact that many publications still use outdated
14
15 504 concepts like 'natural' disasters, although it is internationally acknowledged that disasters are
16
17 505 socially constructed, i.e. their causes are both bio-physical as well as social, economic and
18
19 506 political (Wisner et al., 2004).
20
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23 507 The different challenges for implementing LS-DRR measures that were identified in this
24
25 508 literature review are classified in political, scientific, social, economic, related to disaster risk
26
27 509 management and geographic bottlenecks (Table 6). The main bottlenecks are scientific (30%)
28
29 510 and political (29%) in nature, corresponding to the first two priorities of the Sendai
30
31 511 Framework, i.e. (1) understanding disaster risk and (2) strengthening disaster risk governance
32
33 512 to manage disaster risk (UNISDR, 2015). In the following sections, these two main categories
34
35 513 of bottlenecks are described in detail with examples from our literature review. The other
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37 514 categories can be found in Table 6.
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42 515 [Insert Table 6.]
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47 517 3.3.1 Understanding landslide risk 48 49

50 518 Much progress is made in understanding LS risk in tropical LS-prone countries, i.e. through
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52 519 LS risk assessment, however gaps remain in scientific knowledge. The fact that scientific
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3 520 bottlenecks are cited as the most important in the literature (Table 6) can partly be attributed
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5 521 to the dominance of natural sciences in the literature on LS-DRR.
6
7 522 The most important scientific impediment is the lack of LS inventories and reliable data on
8
9 523 hydro-meteorology (19 pubs). LS are often underreported (Wamsler, 2007) or even missing in
10
11 524 many LS-prone tropical countries (Nadim and Lacasse, 2008; Petley, 2012) because they are
12
13 525 low-intensity, high-frequency hazards and also often considered inseparable from other
14
15 526 natural hazards, such as extreme precipitation, earthquakes and floods (e.g. Jacobs et al.,
16
17 527 2016). For instance in Malaysia, LS are only reported when casualties occur or infrastructural
18
19 528 damage is severe (Althuwaynee et al., 2014). Consequently, most risk assessments tend to
20
21 529 focus on susceptibility mapping instead of the more detailed hazard and risk mapping, while it
22
23 530 is especially the risk aspect that is crucial for providing improved mitigation (Nadim and
24
25 531 Lacasse, 2008). The translation of susceptibility or hazard assessment into risk, requires not
26
27 532 only the identification of element at risks, but also the estimation of loss functions for
28
29 533 expected impacts (Vranken et al., 2015). Realistic LS risk assessments remain a challenge that
30
31 534 is not only restricted to the Global South which indicates a need for the development of
32
33 535 adequate methods (Corominas and Mavrouli, 2011). The Sendai Framework however points
34
35 536 out the need for a persistent knowledge transfer of current disaster risk understandings from
36
37 537 North to South (UNISDR, 2015).
38
39 538 The challenge for LS-DRR is thus not only a lack of available appropriate mitigation
40
41 539 measures (Corominas et al., 2013) but also the poor translation of LS risk assessment into
42
43 540 actual slope management (e.g. DeGraff, 2012; Majid et al., 2007; UNISDR, 2014). This is
44
45 541 also illustrated by the fact that there has been a minimal uptake of LS hazard maps and
46
47 542 vulnerability assessments into policy actions by governments, as argued by Anderson et al.
48
49 543 (2014) based on evidence from Caribbean countries. There is a lack of communicating LS risk
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3 544 from the academic world to decision-makers as well as from decision-makers to groups at risk
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5 545 due to difficulties in translating the scientific content of the models and their associated
6
7 546 uncertainties into more generalised, simplified and practically applicable formats (e.g. Jaiswal
8
9 547 and van Westen, 2013; Leroi, 2005). Risk communication can be seen as a two-way
10
11 548 interactive tool for sharing risk information amongst government officials, researchers and
12
13 549 communities-at-risk (Shaw et al., 2009). It seems that, currently, sharing this risk information
14
15 550 is not interactive nor done in a systematic manner. In many cases risk reduction measures are
16
17 551 not delivered on the ground but rather delivered as secondary output like maps, policies and
18
19 552 (building) codes (e.g. in St. Lucia: Mycoo, 2011). This lack of delivery is partly attributed to
20
21 553 the fact that cost-benefit analyses and inclusive multi-criteria analyses are largely absent in
22
23 554 scientific literature.

24 25 26 27 555 3.3.2 Strengthening landslide risk governance

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30 556 The most restricting political condition is the lack of a stable environment for scientific
31
32 557 development, land use planning and ensuring the continuity of risk reduction activities (11
33
34 558 pubs; Table 6). This might be attributed to several reasons such as the high rates of staff
35
36 559 turnover, changes to institutional mandates, the short lives of some geosciences institutions
37
38 560 and the fluctuating levels of foreign-exchange rates in many LS-prone tropical countries (e.g.
39
40 561 Devoli et al., 2007; Jaramillo, 2008; Künzler et al., 2012). Due to a lack of long-term
41
42 562 commitment by the government, low-budget but relatively long-term and time-consuming
43
44 563 activities are neglected (DFID, 2004; Gue et al., 2009). Especially the lack of secure land
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46 564 tenure rights is considered as a major driver for the misuse of lands (Hofer, 2013).

47
48
49 565 Another challenge is the lack of institutionalisation of LS-DRR, i.e. the integration of LS-
50
51 566 DRR into the national institutional framework (8 pubs). Although this institutionalisation was
52
53 567 one of the main priorities that the HFA strived for, the actual implementation remains

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2
3 568 superficial. Countries with a national slope stability plan as part of their disaster risk
4
5 569 management plan are still scarce. We found evidence of available plans only in Costa Rica
6
7 570 (Andreas and Allan, 2007), Malaysia (Motoyama and Abdullah, 2013) and Sri Lanka
8
9 571 (Bandara and Weerasinghe, 2013). While recently countries are starting to incorporate LS-
10
11 572 DRR into their institutional frameworks (Gue et al., 2009), actual implementation remains
12
13 573 low due to limited law enforcement (e.g. Ahammad, 2011), poor inclusion of local
14
15 574 stakeholders (El-Masri and Tipple, 2002; Santi et al., 2011) and few policy actions that are
16
17 575 based on site-specific scientific knowledge as will be discussed further.

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19
20 576 Setting political priorities on LS-DRR remains challenging in many tropical LS-prone
21
22 577 countries. Nationally a focus remains on post-LS emergency actions (6 pubs). In practice
23
24 578 DRR is only considered after LS events happen and enough media attention is given (e.g.
25
26 579 Hori and Shaw, 2014). A global review on the status of institutional and legislative systems
27
28 580 for LS mitigation in 2009 confirms this focus on response and recovery (Gue et al., 2009).
29
30 581 This is explained by the fact that decision-makers hesitate to invest in projects with
31
32 582 unobservable benefits combined with the absence of cost-effectiveness studies (Anderson et
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34 583 al., 2014) as will be discussed further. Moreover, LS are very localised and often affecting
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36 584 marginalised population thus attracting considerably less political attention compared to
37
38 585 large-scale events such as floods or drought.

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44 45 46 587 3.4 Methodological limitations

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48 588 This literature review is affected by some limitations. A bias in the dataset exists because only
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50 589 peer-reviewed publications with English abstracts have been consulted. Many LS-DRR efforts
51
52 590 are published in the national language of the country affected or not published in scientific

1
2
3 591 journals but only as reports by governments, NGOs, private sector or not published at all like
4
5 592 indigenous knowledge or ‘silent evidence’ (e.g. Taleb, 2007). Other LS studies (Gokceoglu
6
7 593 and Sezer, 2009; Gutiérrez et al., 2010; Sepúlveda and Petley, 2015) have however used
8
9 594 similar methods as this literature review. Furthermore, several observations and trends are
10
11 595 based on small numbers of publications, so the reported statistics should be considered
12
13 596 indicative.

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15
16 597 To investigate this bias, an additional survey of the grey literature for Uganda was made to
17
18 598 check for inconsistencies. Including grey literature shows that looking at peer-reviewed
19
20 599 scientific literature tends to neglect the implemented governance and awareness components
21
22 600 of LS-DRR in the case of Uganda (Fig. 8). This Ugandan case-study thus illustrates that
23
24 601 recommendations made by authors of peer-reviewed publications do not necessarily align
25
26 602 with those made by governments or civil society actors. The clear preference for
27
28 603 implementing LS risk assessment is however visible in both reviews.
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33 34 605 4. Conclusions and recommendations

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36
37 606 The literature on landslides (LS) and landslide disaster risk reduction (LS-DRR) is rapidly
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39 607 increasing worldwide (Gutiérrez et al., 2010; Wu et al., 2015). Our review shows that:

- 40
41
42 608 – The factors that influence the number of publications on LS and LS-DRR per country
43
44 609 are the absolute physical exposure of people to LS ($\rho = 0.77; 0.73$), the population (ρ
45
46 610 $= 0.55; 0.61$) and –to a lesser extent- the HDI of a country ($\rho = 0.35; 0.32$).
- 47
48
49 611 – The ratio of publications on LS-DRR versus publications on LS for LS-prone tropical
50
51 612 countries for the period 2005-2015 does not differ much between these countries
52
53 613 (0.28).

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3 614 – The vast majority (0.64) of all publications on landslide risk reduction in the tropics
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5 615 was published in journals or proceedings relating to ‘natural sciences’.
6
7

8 616 Our review further clarifies the main recommended and implemented LS-DRR measures to
9
10 617 date based on the compiled classifications of Twigg (2007) and Vaciago (2013; Table 4).
11
12 618 More specifically, it shows that:
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15 619 – A significant fraction (0.30) of all potential LS hazard reduction measures (as
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17 620 classified by the SafeLand project) are neither recommended nor implemented for the
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19 621 tropics.
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21
22 622 – The most recommended LS-DRR component (expressed as a fraction of all measures
23
24 623 cited) for the tropics is ‘risk management and vulnerability reduction’ (0.38), while the
25
26 624 most implemented component is ‘risk assessment’ (0.57).
27

28
29 625 – The ratio of implemented versus recommended LS-DRR measures in the tropics is
30
31 626 rather low for most LS-DRR components (‘risk management and vulnerability
32
33 627 reduction’: 0.25; ‘preparedness and response’: 0.27; ‘governance’: 0.36; ‘knowledge
34
35 628 and education’: 0.47), except for ‘risk assessment’ (3.01).
36

37
38 629 – The most cited bottlenecks for implementing LS-DRR measures (expressed as a
39
40 630 fraction of all bottlenecks cited) are scientific (0.30) and political (0.29).
41

42
43 631 Based on this study, several research needs for LS-DRR can be distilled. Overall, this review
44
45 632 shows that a lot of research has focussed on understanding landslide susceptibility and
46
47 633 hazards in relation to the bio-physical factors that control them. However, quantitative
48
49 634 assessments of the impacts of landslides are much rarer. Also scientific assessments of the
50
51 635 effectiveness of implemented DRR measures is largely lacking in the current scientific
52
53
54 636 literature. Nonetheless, such information is crucial to support cost-benefit analyses and
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3 637 research on how to effectively translate risk assessment into risk reduction measures. This
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5 638 will require multi-criteria analyses identifying the most effective LS-DRR measures as a
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7 639 function of the spatial scale, the type of LS, the (potential) impact, the underlying root causes
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9 640 and bottlenecks which are currently lacking at national and lower levels.
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11 641 Moreover, it appears that the responsibility of scientists cannot end at the identification and
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13 642 characterisation of LS hazard and risk, or the recommendation of generic DRR measures.
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15 643 Effectively reducing LS risks will not only require better scientific insights, but also efforts to
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17 644 communicate and transfer scientific research results to policy makers and the population at
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19 645 risk. Involving stakeholders at all stages of the scientific research, i.e. from problem
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21 646 identification to delivery of the most practical results, is crucial to promote ownership and to
22
23 647 ensure more site-specific and effective efforts. As landslide research currently remains mainly
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25 648 driven by earth scientists, this will require initiatives in developing trans-disciplinary
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27 649 approaches that are able to go beyond the analysis of the physical drivers of landslides, but
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29 650 integrate the social, political, cultural and economic dimensions of disaster risk reduction in
30
31 651 order to identify and characterise the effectiveness of specific DRR measures (Cutter et al.,
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33 652 2015). Hence, earth scientists should actively seek interactions with experts in social sciences
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35 653 and grass-root organisations in order to bridge the gap between the improved understanding of
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37 654 landslide hazard and the effective reduction of landslide risk.
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3 Fig. 1. World map with the absolute physical exposure of people to landslides, expressed
4 as the expected annual average number of persons exposed in 2010, per pixel (5x5km)
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8 (adapted from NGI, 2013).
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11 Fig. 2. Scatter plots of the factors determining the number of publications on landslides
12 per country (#pubs LS/co) in Scopus for the period Jan. 2005 – Jan. 2015 ($p < 0.001$; $n =$
13 85) indicating the linear trend line and the coefficient of determination, (a) the absolute
14 physical exposure of people to landslides (# inhabitants/year) of the tropical landslide-
15 prone countries, (b) the population (# inhabitants) of the tropical landslide-prone
16 countries, (c) the HDI of the tropical landslide-prone countries, and (d) the number of
17 publications on landslide risk reduction (# pubs LS-DRR) of the tropical landslide-prone
18 countries. The figures on the left present the entire dataset, while the figures on the right
19 correspond to the zoom (indicated with a box in the figures on the left) (Note: Visual
20 outliers are labelled).
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35 Fig. 3. (a) World map with the number of publications on landslides (# pubs LS) reported
36 in Scopus of the tropical landslide-prone countries for the period Jan. 2005 – Jan. 2015,
37 and (b) World map with the number of publications on landslide risk reduction (# pubs
38 LS-DRR) reported in Scopus of the tropical landslide-prone countries for the period Jan.
39 2005 – Jan. 2015. Numbers indicate the # pubs for countries with more than 15
40 publications (for pubs LS) and more than 4 publications (for pubs LS-DRR).
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50 Fig. 4. Number of publications on landslide risk reduction (# pubs LS-DRR) of tropical
51 landslide-prone countries in Scopus for the period Jan. 2005 – Jan. 2015 grouped
52 according to the spatial scale of analysis ($n = 382$; NA is Not Available).
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4 Fig. 5. Distribution of the number of publications on landslide risk reduction (# pubs LS-
5 DRR) in Scopus for the period Jan. 2005 – Jan. 2015 according to the authors' country of
6 origin, (a) Tropics (n = 382), (b) Africa (n = 24), (c) Asia-Pacific (n = 222) and (d) Latin
7 America (n = 136) (NA = Not Available).
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13 Fig. 6. Distribution of the publications on landslide risk reduction (# pubs LS-DRR) in
14 Scopus for the period Jan. 2005 – Jan. 2015 according to the authors' organisation, (a)
15 Tropics (n = 382), (b) Africa (n = 24), (c) Asia-Pacific (n = 222) and (d) Latin America
16 (n = 136) (U = University, G = Government, NGO = Non-governmental organisation, P =
17 Private sector, NA = Not Available, M = Multiple organisations).
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26 Fig. 7. Percentage of the number of publications on landslide risk reduction (# pubs LS-
27 DRR) in Scopus for the period Jan. 2005 - Jan. 2015 that cite the recommended landslide
28 risk reduction components (left column) and the implemented landslide risk reduction
29 components (right column) (see Table 4). (a) Total percentages of the number of
30 publications reporting recommended (total number of citations is 709, reported in 225
31 individual papers) and implemented landslide risk reduction components (total number of
32 citations is 461, reported in 245 individual papers). Subfigures (b-d) show these results
33 for the specific sub-regions.
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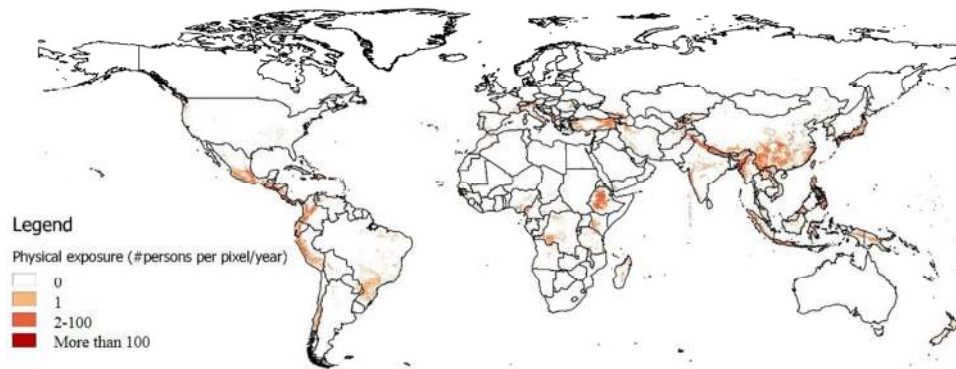
45 Fig. 8. Number of publications on landslide risk reduction (# pubs LS-DRR) reporting (a)
46 recommended and (b) implemented landslide risk reduction (LS-DRR) components (see
47 Table 4) for Uganda based on grey literature and peer-reviewed literature on landslide
48 risk reduction in Scopus (black bars) or based on peer-reviewed literature only (white
49 bars), (G = Governance; RA = Risk Assessment; K&E = Knowledge and Education;
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R&V = Risk management and Vulnerability reduction; P&R = Preparedness and response).

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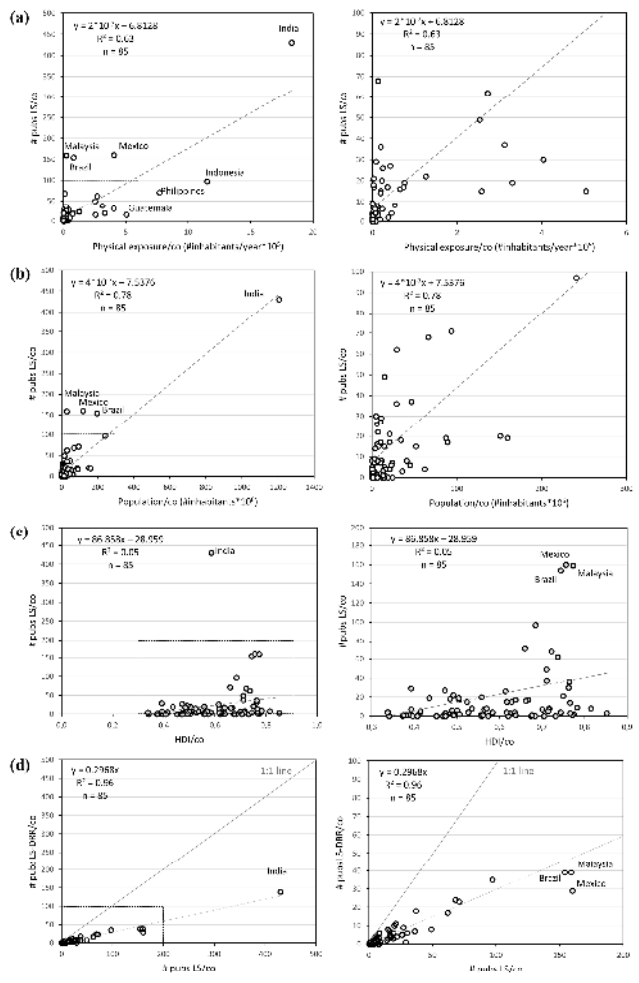
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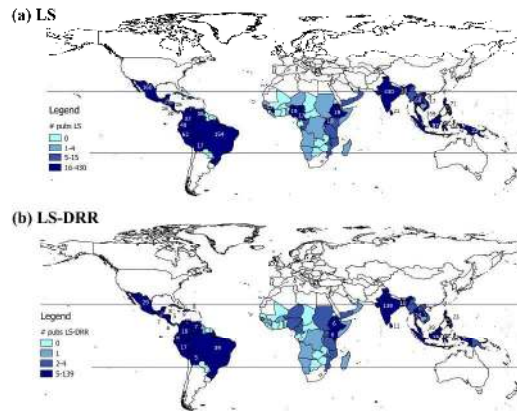
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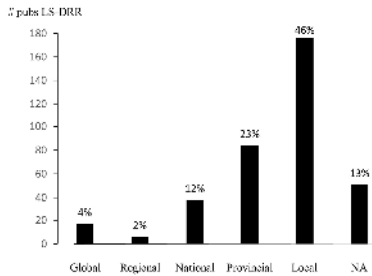
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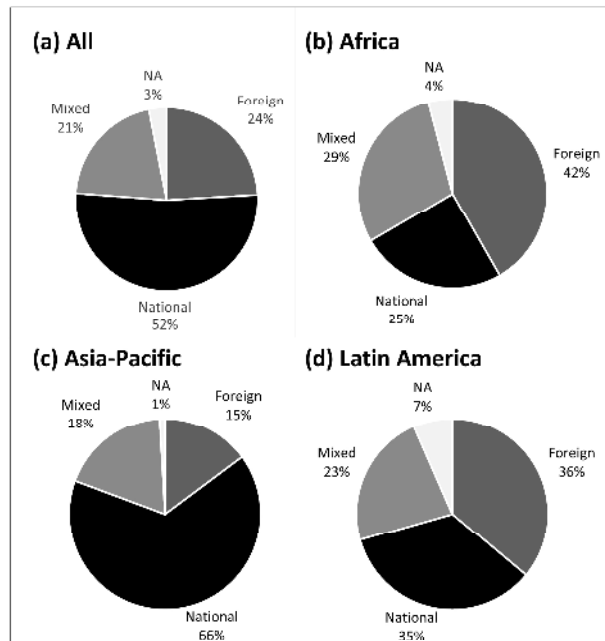
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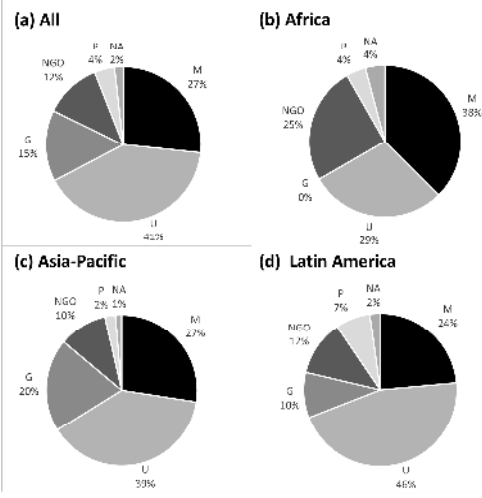
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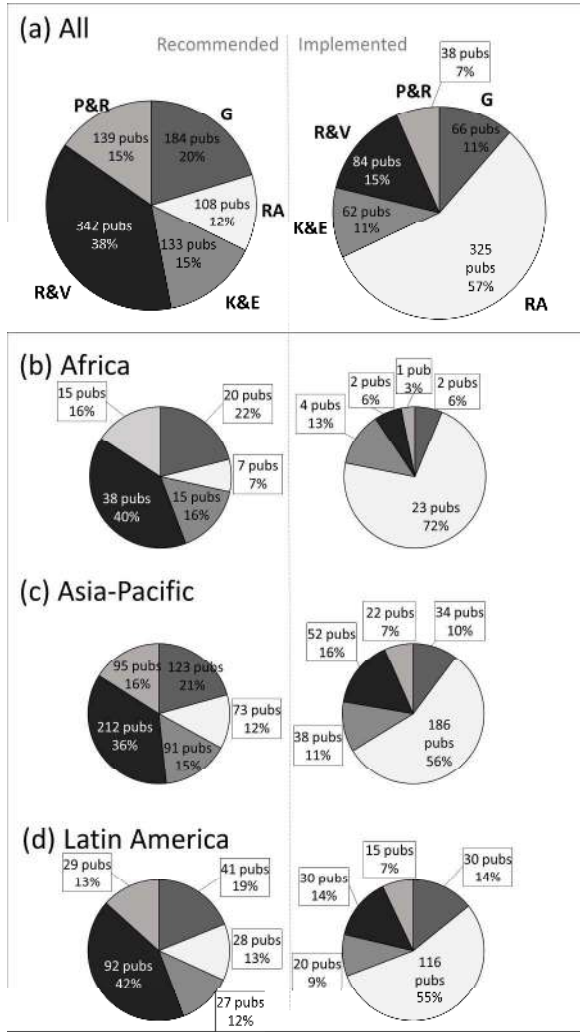
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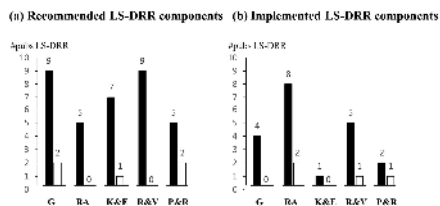
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Table 1. Overview of landslide-prone and not landslide-prone tropical countries based on global and region-specific datasets with, between brackets, the number of publications on landslides and on landslide risk reduction respectively in Scopus for the period between Jan. 2005 and Jan. 2015. An asterix ‘*’ means that the countries do yield landslide publications in Scopus for the period between Jan. 2005 and Jan. 2015 (Note: Since the search period for articles was between Jan. 2005 and Jan. 2015, South Sudan was not considered).

Landslide-prone tropical countries (n = 99)

Angola (4;1), Antigua & 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 & 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 & 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)

Not landslide-prone tropical countries (n = 39)

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 & Nevis, St. Vincent & the Grenadines*, Tokelau, Tonga, Turks & Caicos Islands, Tuvalu, Wake Island, Wallis & Futuna

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 Web of Science, Scopus and Google Scholar for the period Jan. 2005 - Jan. 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 means Not Applicable)

		<i>Average</i> #pubs/co	<i>Median</i> #pubs/co	<i>Total</i> #pubs	<i># countries</i> <i>with pubs</i>
Scopus <i>(SC)</i>	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 <i>(WoS)</i>	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 <i>(GS)</i>	pubs LS (1)	8	0	753	46
	pubs LS-DRR (2)	1	0	68	19
	Ratio (2)/(1)	0.13	NA	0.09	NA

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)

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

Table 4. Number of publications (#pubs) in Scopus for the period Jan. 2005 – Jan. 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 means Not Applicable).

<i>DRR component</i>	<i>Landslide risk reduction measures</i>	<i>I</i>		<i>R</i>		<i>I/R</i>
		<i>#pubs</i>	<i>%</i>	<i>#pubs</i>	<i>%</i>	
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	Unspecified	2	0	19	2	0.11
	Surface protection; erosion control of landslide-toe	7	1	49	6	0.14
	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
	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

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 Jan. 2005 – Jan. 2015 recommending (R) a specific ‘risk management and vulnerability reduction’ measure to reduce landslide risk (total number of citations, reported in 169 individual publications, is 342) and describing that a specific ‘risk management and vulnerability reduction’ measure to reduce LS risk is being implemented (I) (total number of citations, reported in 52 individual publications, is 84).

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 (hydroseeding, 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
	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)			
	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

For Peer Review

Table 6. Number of publications on landslide risk reduction (# pubs LS-DRR) in Scopus for the period Jan. 2005 – Jan. 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	