Evaluating the impact of climate change on landslide occurrence, hazard, and risk: from global to regional scale

Stefano Luigi Gariano[1,2] and Fausto Guzzetti[1]

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1) CNR IRPI, Perugia, Italy (stefano.gariano@irpi.cnr.it); 2) University of Perugia, Department of Physics and Geology, Perugia, Italy.

Introduction

According to the 5th report of the Intergovernmental Panel on Climate Change (IPCC), "*warming of the climate system is unequivocal*". The influence of climate changes (CC) on slope stability and landslides is also undisputable. Nevertheless, the quantitative evaluation of the impact of global warming, and the related changes in climate, on landslides remains a complex question to be solved. The evidence that climate and landslides act at only partially overlapping spatial and temporal scales complicates the evaluation.

1. Literature review

We analysed more than 100 papers dealing with the effects and the consequences of CC and landslides published since 1983 (*Gariano and Guzzetti, 2016*).

The study of the impacts of CC on landslides is attempted adopting modelling, empirical, or combined approaches. Two groups of empirical approaches can be singled out. A first empirical approach (namely historical analysis) compares catalogues of historical landslide occurrences with climatic records, chiefly rainfall and temperature, covering a few to many decades, typically in the last two centuries. A second empirical approach exploits paleo-environmental data to reconstruct records of ancient landslides and to analyze periods of increased/decreased landslide activity.

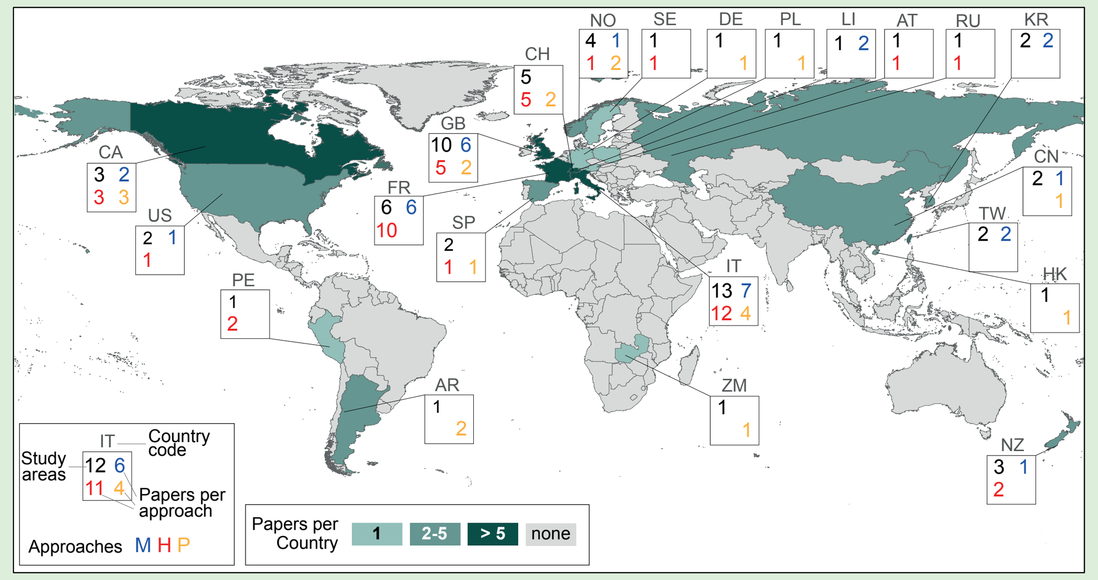

Figure 1. Geographical distribution of landslide-climate studies. For each country, the number of study areas and the number of papers for three different approaches are given. Approaches: M, modelling approach; H, historical analysis; P, analysis of paleo landslide evidences.

Five continents are represented, with a large number of studies in Europe (69), followed by North America (10), Asia (7), South America (4), Oceania (3), and Africa (1). The Alps are the most investigated physiographic area.

2. Impact of climate on landslides

The influence of climate and its variations on landslides can be classified broadly as: (i) local / regional (or global), (ii) of short- / long-term impact, and (iii) direct / indirect.

Local impacts influence the stability of a single slope or of an individual landslide. Regional influences affect landslide occurrence and hazard in areas ranging from a few hundreds to several thousands of km² (a province, a country, a broad geographical region).

Short-term climate effects influence landslides in periods ranging from a few years to one/two centuries, whereas long-term effects cover longer periods in the range from a few centuries to several thousands of years

Direct climate impacts influence parameters that directly control landslide occurrence, like a change in rainfall regime that influences the amount of rainfall that can result in landslides. Indirect climate effects influence environmental and landscape conditions that, in turn, affect landslides (e.g., land use/cover).

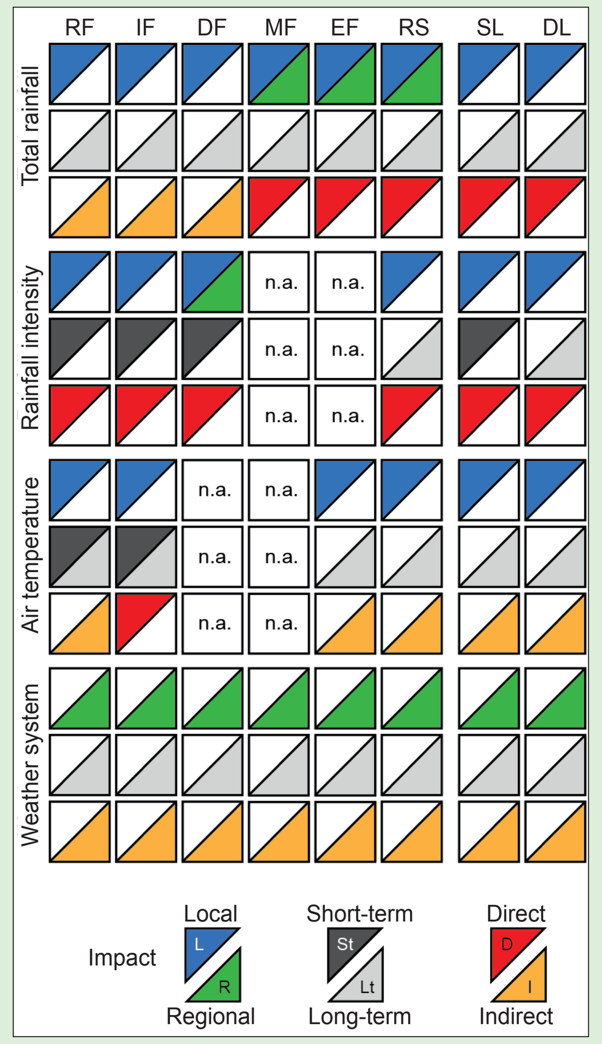

Figure 2. Local / regional, short- / long-term, direct / indirect expected impact of 4 climate variables (total rainfall, rainfall intensity, air temperature, weather system) on 8 landslide types (RF, rock fall/avalanche; IF, ice fall/avalanche; DF, debris flow; EF, earthflow; MF, mudflow; RS, rock slide; SL, shallow; DS, deep-seated landslide).

3. Changes in landslide hazard

We assume landslide hazard H_L as the joint probability of landslide size $P(A_L)$, of landslide occurrence in a period $P(N_L)$, and of landslide spatial occurrence S:

$$H_L = P(A_L) \times P(N_L) \times S$$

1) $P(A_L)$ *will not change* significantly in time (valid if the mechanical properties of the materials - particularly cohesion - will not change).

2) $P(N_L)$ depends on the frequency of the triggers. The frequency of seismic triggers *will not change* in the period considered for CC; hydrological conditions and meteorological triggers *will change*; human triggers may also *change*, in response to changes in economy, agricultural or forest practices.

3) S depends on terrain terrain conditions (elevation, slope, curvature) and geological conditions (rock type, structure, faults, seismicity), which *will not change* in the period considered for CC. S depends also on other environmental conditions (land use/cover, forest cover, agricultural practices), which *will change* in response to the changing climate. The hydrological conditions, the precipitation regime and the precipitation patterns *may change*, influencing landslide susceptibility.

4. Global scale

We prepared a global map showing the expected changes in the abundance or activity of 4 landslide types produced by expected CC (*Gariano and Guzzetti, 2016*).

The projected increase in surface temperature is expected to result in *more intense and frequent rainfall events*, in particular *over most of the mid-latitude and wet tropical regions*. In these areas, *shallow landslides* (e.g., rock falls, debris flows, debris avalanches, and also ice falls and snow avalanches in high mountain areas) *are expected to increase*.

Given the fact that shallow landslides, which often are very to extremely rapid, are a primary cause of fatalities, we expect that, in these areas, landslide *risk to the population* and the total number of *people exposed to landslide risk will increase*.

In the same areas, the degree of activity and the occurrences of new *deep-seated landslides are expected to decrease*. Extremely to moderately slow deep-seated landslides (e.g., earthflows, mudflows, complex and compound slides) generally do not pose a serious threat to human life. Hence, their predicted reduced activity will not decrease landslide risk to the population significantly, but it is expected to contribute to *reducing landslide impact and the related economic damage*.

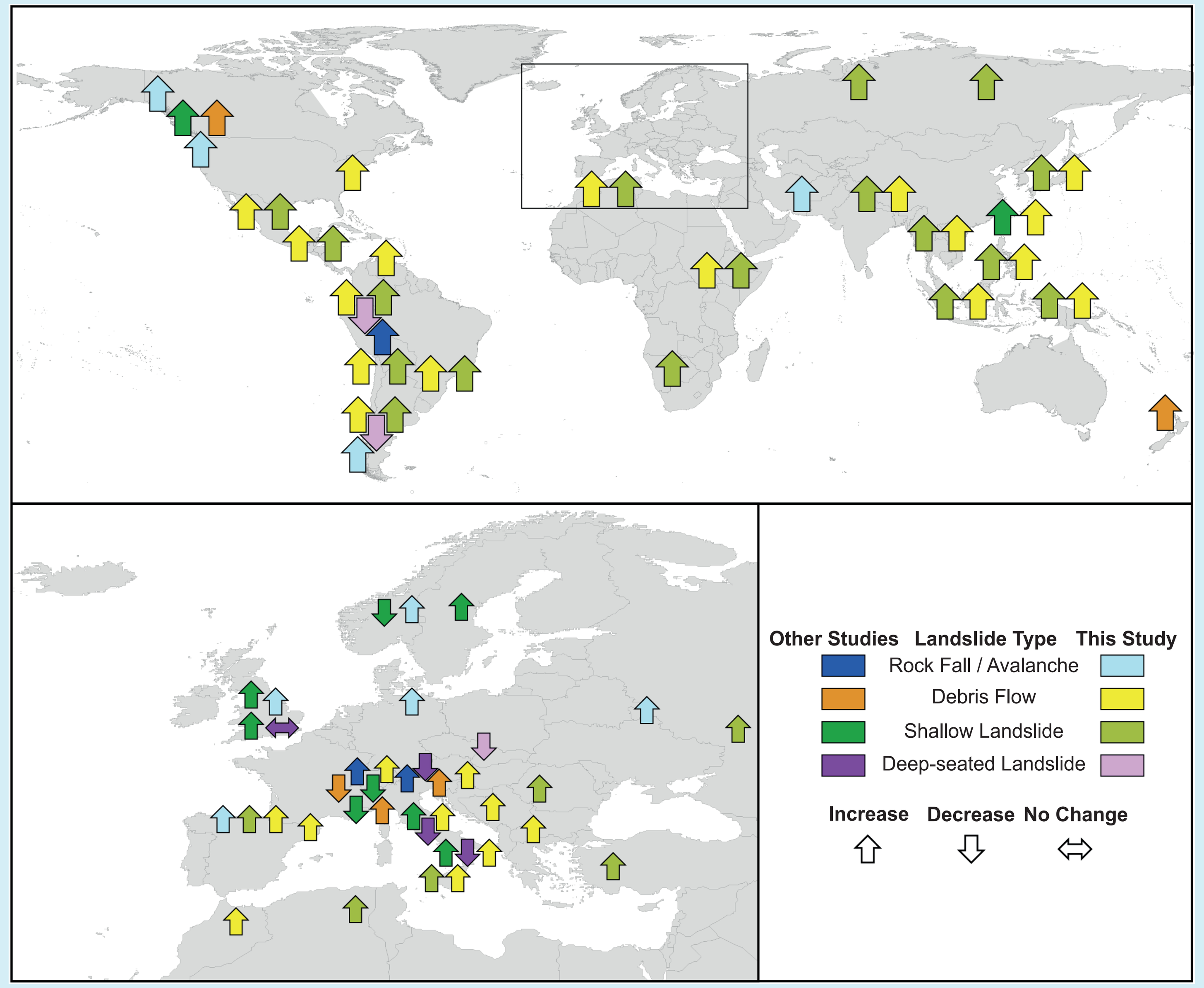

Figure 3. Map shows general areas of expected variations in the abundance or activity of 4 landslide types (rock falls, debris flows, shallow landslides, and deep-seated landslides), driven by the projected CC. Dark colours are projections from the literature and light colours are projections from this study.

5. Regional scale

We defined a method for the evaluation of future variations in the occurrence of rainfall-induced landslides, in response to changes in rainfall regimes, at a regional scale.

We exploited a catalogue with information on the occurrence of rainfall-induced landslides and daily rainfall records. Furthermore, we used high-resolution climate projections based on different IPCC scenarios. Based on reliable correlations between landslide occurrence and weather variables estimated in a reference period, we assessed future variations in rainfall-induced landslide occurrence at regional and municipal scales.

We also investigate past and future variations in the impact of rainfall-induced landslides on the population, comparing the (observed and expected) number of landslides with the (observed and expected) size of the population in the study area (*Gariano et al. 2015; 2017*).

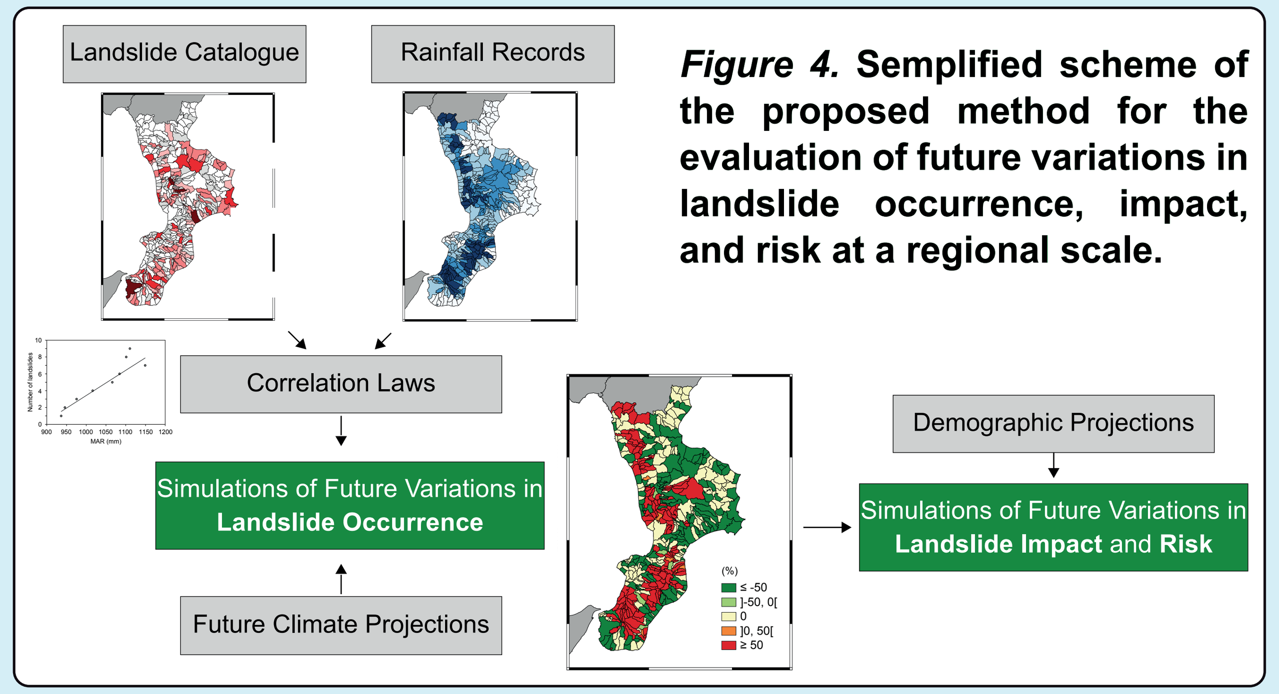

Figure 4. Semplified scheme of the proposed method for the evaluation of future variations in landslide occurrence, impact, and risk at a regional scale.

Hazard: $H = P(A) \times P(N) \times S$

Risk: $R = H \times E \times V$

Simplified formulas for Risk and Impact

Risk: $R = \#L \times Pop$

Number of landslides — Number of inhabitants

Impact: $I = \#L / Pop$

We applied the method in the Calabria region, southern Italy, where we had available a catalogue of 603 rainfall-induced landslides occurred in the period 1981-2010 and daily rainfall data. We considered the mean variations between a 30-year future period (2036–2065) and the reference period (1981-2010) in 3 variables assumed as proxy for landslide activity: annual rainfall, seasonal cumulated rainfall, and annual maxima of daily rainfall. To analyse variation in landslide impact to the population, we used demographic data available from national Census conducted by the Italian National Institute of Statistics. We found an expected *increase* in the average regional *variation in rainfall-induced landslide occurrence* and in *landslide impact on the population*, for the period 2036–2065.

The proposed *method* is *quantitative* and *reproducible*, thus it can be applied in similar regions, where adequate landslide and rainfall information is available.

Conclusions

Global warming has direct and indirect impacts on multiple natural and human induced factors, which in turn *can condition landslide occurrence, hazard, and risk*. The natural and human induced drivers have complex interactions and feedbacks, which are difficult to investigate and quantify even in a "stable" climate. Determining if and where landslide risk is excepted to increase or decrease in response to CC remains a difficult and *uncertain task* that needs more investigations.

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stefano.gariano@irpi.cnr.it