Integrated grey-green management of avalanche risk: Economic and ecologic evidences from the Western Italian Alps

DOI:10.1016/j.ijdrr.2020.101502

(Article begins on next page)

Manuscript Details

Manuscript number	IJDRR_2020_599
Title	State-of-the-art on ecosystem-based solutions for disaster risk reduction: the case of gravity-driven natural hazards in the Alpine region
Article type	Review Article

Abstract

Alpine regions are affected by various natural hazards. Due to the high density of settlements in these areas, natural hazards constitute a risk element for the local populations, therefore risk management is fundamental. The options for hazards management consist in structural measures, land use planning and EcosystemBasedSolutions (EbS). Technical measures while immediately effective, have emerged as insufficiently adaptable to changes in environmental conditions. On the contrary, EbS have the potential to adjust to the challenges driven by global environmental change. This is the reason why EbS have increasingly gained attention. In this review, we address the role of EbS in Disaster Risk Reduction (Eco-DRR). The review is composed by two main parts: (i) a quantitative bibliometric analysis followed by (ii) a qualitative review. The first part focused on the quantitative analysis of peer-reviewed publications to investigate general publication trends. This bibliometric analysis served as a basis to select articles for the subsequent qualitative analysis in which the parameters addressed were mainly: the type of natural hazard studied, the characteristics of the EbS, the development of alternative scenarios, the involvement of the stakeholders and the monetary evaluation of the measures The results highlight an increase in number of EbS-related publications from 1980 to 2019. The qualitative analysis, however, revealed that the involvement of stakeholders and the economic evaluation of EbS is still lacking. We conclude that filling this research gap might help to foster a wider adoption of ecosystem-based solutions for disaster risk reduction across mountainous areas.

Keywords	Risk management; Eco-DRR; Protection Forest; avalanche; rockfall; landslide.

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State-of-the-art on ecosystem-based solutions for disaster risk reduction: the case of gravity-driven natural hazards in the Alpine region

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Abstract

Alpine regions are affected by various natural hazards. Due to the high density of settlements in these areas, these natural hazards constitute a risk element for the local populations, therefore risk management is fundamental. The options for the management of these hazards consist in structural measures, land use planning and ecosystem-based solutions (EbS). Structural technical measures, such as avalanche snow bridges or rockfall nets, while immediately effective, have emerged as insufficiently adaptable to changes in environmental conditions. On the contrary, EbS have the potential to adjust to the challenges driven by global environmental change. This is the reason why, over the past few years, EbS have increasingly gained attention.

In this review, we address the role of EbS in Disaster Risk Reduction (Eco-DRR). The review is composed by two main parts: (i) a quantitative bibliometric analysis followed by (ii) a qualitative review.

The first part focused on the quantitative analysis of peer-reviewed publications (Scopus database) to investigate general publication trends. This bibliometric analysis served as a basis to select articles for the subsequent qualitative analysis in which the parameters addressed were mainly: the type of natural hazard studied, the characteristics of the EbS, the development of alternative scenarios, the involvement of the stakeholders and the monetary evaluation of the measures

The results highlight a strongly increasing number of EbS-related publications from 1980 to 2019, particularly since the turn of the millennium. The qualitative analysis, however, revealed that the involvement of stakeholders and the economic evaluation of EbS is still lacking. We conclude that filling this research gap might help to foster a wider adoption of ecosystem-based solutions for disaster risk reduction across mountainous areas.

Keywords

Risk management, Eco-DRR, Protection Forest, Avalanches, Rockfall, Landslides, Debris flow

1. Introduction

Mountainous areas have always been subject to natural hazards. The great geodiversity, the variation of steep gradients and the hydroclimatic variability of European mountains, and in particular of the Alps, results in a high variation of natural hazard processes and their consequences [1]. These hazards are related both to the cryosphere, such as snow avalanches, occurring in the Alps during winter and springtime [2], and to the geosphere, with precipitation-driven events, such as landslides, debris flows and rockfalls [3]. Globally, scientists have focused their attention on these hazards ever since the 18th century, providing data which still influence the current scientific debate on the matter. In a recent publication by Keiler and Fuchs [1], an overview of hazard management in mountainous areas was presented, highlighting how the concept of risk management was introduced as a core constituent beginning in the 19th century [4], and already addressed acute and fundamental topics such as vulnerability and the human impact of such events.

The Alps are among the most highly populated mountainous areas of the world, with more than 14M inhabitants and densely settled communities [5]. These features, given the frequent occurrence of the above mentioned natural hazards, makes hazard and risk management a matter of primary importance [6]. In the early 20th century, hazard management consisted mostly of the construction of technical measures in the upper tracts of torrent catchments, to avoid mass erosion and the detachment of avalanches. This approach mainly focused on the hazard instead of elements subject to risk, and only successively these types of structures were accompanied by mitigating measures in the runout area of the events, built to deflect the processes [7]. The broader concept of risk only emerged in the latter 20th and early 21st centuries in mountain hazard management, taking into consideration not only structural adjustments to deal with the hazards, but also non-structural ones [8,9]. Risk management has gradually morphed into a multidisciplinary approach, taking into account not only the scientific knowledge of the hazard features and the technical mitigation measures, but also the socio-economic effects of said hazards. This has led to a wider use of the concepts of exposure and vulnerability, prompting an increased awareness of approaches to be used in land use planning [10,11].

Currently, the main instruments used to manage risk in mountainous areas consist of 1) structural measures designed to prevent the hazard or to protect the goods at risk in the track and runout area and 2) mapping of areas at risk to implement forms of land use limitation [10,12]. In the context of expansion of settlements and activities in mountainous areas, land use restrictions might undermine the quality of life. Furthermore, the adoption of technical structural measures might be constrained by their high implementation and maintenance costs and by the inability of such measures to adapt to changes in the hazard features [15,16], especially in light of the rapidly occurring challenges caused by climate change [17].

In this context, an increased focus has been directed towards ecosystem-based solutions (EbS) [18,19]. In particular, as far as mass movements are concerned, a valid alternative and complement to the aforementioned hazard mitigation measures is represented by protection forests [6]. Protection forests are stands whose primary function is to protect people or assets against natural hazards [20], therefore not only providing a general protective effect, e.g. by reducing soil erosion and the transportation of sediments into the catchments; but also direct protection for assets at risk [21]. Ecosystem-based disaster risk reduction (Eco-DRR) solutions act directly against the hazards [22], preventing them from happening (e.g. the role of the forest in the release areas of avalanches Moos et al., 2018) or mitigating their impact in the runout zone (e.g. the role of forest against rockfall, Berger and Rey, 2004). These Eco-DRR measures, other than providing an efficient mitigation effect against multiple hazards [23], are also an efficient protective solution, in consideration of the expected hazard modifications due to climate change, providing a higher grade of adaptation [24,25].

Several literature reviews on the use of EbS to address different hazards have recently been published in scientific literature; however, their focus is on single hazards, such as shallow landslides [26] or on urban areas [27]. Several reviews focused on mountainous regions, nonetheless, they addressed a broader range of ecosystem services provided by mountain ecosystems, and not narrowly natural hazard regulation [28]. Others have a more quantitative perspective, analysing the influence of the forest in reducing the hazard effects [6]. Overall, there is no systematic review on the use of EbS for disaster risk reduction that considers multiple natural hazards occurring in mountain areas. Therefore, the overall objective of the present study is to analyse to what extent EbS have been studied as potential risk reduction measures in mountain environments, such as the Alps. In this paper, our aim was to analyse the state-of-the-art of the research, focusing on the following points:

1. Eco-DRR: the selected studies include ecosystem-based disaster risk reduction solutions within the range of protection measures considered, promoting the sustainable use and management of ecosystems as a means to reduce extreme events. In this regard, we were interested in analysing the management strategies of these ecosystems, their technical characteristics (e.g. species composition), their effectiveness in hazard risk reduction and the influence of disturbances on such effectiveness. The selection of publications should not only provide an overview on how the hazard release and run-out is influenced by EbS but must also examine how the EbS are adopted from a risk management perspective. This review also aims to verify if the currently available literature on the topic, tests or suggests approaches such as stakeholder involvement and economic evaluation.
2. Mountain ecosystem: in particular we focused on risk mitigation in the Alpine region [29], as it is one of the most densely populated mountainous areas of the world [5]. The review aimed to analyse the distribution of the studies in this research field over different countries.
3. Gravity-induced natural hazards: mass movements have been considered, more specifically avalanches, rockfalls, landslides and debris flows, due to their frequency in the Alps, their severe impact on the population and the capacity of ecosystems such as protection forests to prevent and mitigate such hazards. In particular, the review aimed to verify if the available literature is focusing equally on all the different types of mass movements.

The following review is divided into two phases: a bibliometric analysis and a qualitative review. The bibliometric analysis aimed to gain an insight on the general trend of papers, published over time in scientific literature in this research field. Moreover, it served as a first step to select the articles to be reviewed in the subsequent qualitative part of the analysis. The objective of the qualitative review was to analyse the studies conducted by means of a pre-defined set of questions. This allowed the research topics to be synthesized and thus gain an exhaustive coverage of current literature, in order to identify the strengths of the available studies and highlight any research gaps on which to focus further research.

2. Methods

The analysis followed a mixed-method approach, represented by the combination of a quantitative bibliometric analysis and of a qualitative review. The methodology adopted was three-fold: firstly, we conducted a quantitative bibliometric analysis in the Scopus database; subsequently, the search was integrated with WebOfScience (WOS) results, and finally a qualitative analysis of the publications was performed. We adopted a systematic approach throughout all the steps in order to guarantee reproducibility and to avoid bias. Search terms were selected to compose the query strings; they were grouped in three main clusters, corresponding to the topics on which the research focuses (see Table 1): 1) gravity-induced natural hazards, 2) risk management and 3) ecosystem-based solutions. After being selected, the search terms were evaluated on the basis of a first plausibility check of the results. To reduce misleading results the strings were adjusted: for instance, the search term "avalanche" was delivering results regarding electron avalanches, a topic not related to our field of research; consequently, the search term was changed to "snow avalanche*".Moreover, first qualitative plausibility checks revealed that the subordinate term "Landslide*" was not only used for publications that dealt with landslides of slide-type movement, but also for research that specifically addressed rock falls or debris flows (without mentioning these terms in the title, abstract or keywords). Thus, the observed high number of landslide studies should be interpreted with care. The query strings were searched on the Scopus database in “Titles, Abstract and Keywords” of published articles, reviews, book chapters and conference proceedings, limiting the search to the English language. The search was conducted in January 2020 and therefore included all the relevant documents published in 2019.

Table 1 - Terms selected to compose the query strings

Topic Group	Search terms
Gravity-induced natural hazards	Snow avalanche* Debris-flow* Rock fall* (or Rockfall*) Landslide*
Risk management	Risk Exposure Vulnerability Hazard management Mitigation Disaster Risk Reduction (or DRR)
Ecosystem-based solutions	Nature-based solution* Ecosystem-based approach* Ecosystem-based solution* ECO-DRR Protection forest Protect* function Protect* effect

Different searches were carried out in the Scopus database: the first search combined the first two groups of terms (those regarding gravitational natural hazards and risk management) in order to identify the publications focusing on the mitigation, analysis or management of risks related to the natural hazards of interest. The second search also included the EbS terms, in order to identify how many of the previously selected papers focused specifically on ecosystem-based solutions. The search terms belonging to different topic groups were linked with the Boolean operator “AND”, whereas the search terms belonging to the same group were linked using the Boolean operator “OR”. This allowed documents to be found that that included at least one term from each group of topics. Therefore, the “AND” Boolean operator in the second search, allowed the selection of those publications that were already part of the first search results but which had a more specific focus on Eco-DRR.

The query strings adopted for the two searches are the following:

First search: TITLE-ABS-KEY(("snow avalanche*" OR "debris-flow*" OR "rock fall*" OR "Rockfall*" OR "landslide*") AND ("risk" OR "exposure" OR "vulnerability" OR "hazard management")) AND (EXCLUDE (PUBYEAR,2020)) AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"ch") OR LIMIT-TO (DOCTYPE,"re") OR LIMIT-TO (DOCTYPE,"cr")) AND (LIMIT-TO (LANGUAGE,"English"))

Second search: TITLE-ABS-KEY (("snow avalanche*" OR "debris-flow*" OR "rock fall*" OR "Rockfall*" OR "landslide*") AND ("risk" OR "exposure" OR "vulnerability" OR "hazard management" OR "mitigation" OR "DRR" OR "disaster risk reduction") AND ("protection forest*" OR "protect* function" OR "protect* effect" OR "ECO-DRR" OR "nature-based solution*" OR "ecosystem-based approach*" OR "ecosystem-based solution*" OR "green infrastructure*")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "cr")) AND (EXCLUDE (PUBYEAR , 2020)) AND (LIMIT-TO (LANGUAGE , "English"))

The trend of publications was analysed and compared with the total number of papers indexed on Scopus throughout the years. In order to obtain an estimate of the total amount of papers, as this information is not available directly, the word “the” was used as a search term, as it is the most common English word.

For the subsequent bibliographic review, the same search was performed using WOS to see if any additional papers could be found that had not yet been indexed on Scopus. The results were added to those extrapolated from Scopus. Successively, through an abstract analysis, papers concerning the Alps were selected, read and analysed (Figure 1). In order to critically discuss the content of each article and gain some relevant information, we defined a criterion to review each paper: a list of fixed characteristics to be searched within each paper analysed in the review. These elements were selected in order to derive relevant information about the topics targeted by the review, with a special focus on how Eco-DRR were considered and analysed in each study. The complete criteria adopted to qualitatively review each article is presented below:

1) Natural hazard considered (Avalanche/Rockfall/Landslide/Debris flow);
2) Eco-DRR features:
   2.1. Management activities;
   2.2. Specific composition
   2.3. Analysis of their effectiveness in risk mitigation;
3) Uncertainties considered (fires/pests/hazard interaction/etc.);
4) Development of alternative scenarios to test different hypothesis;
5) Degree of stakeholder involvement and methodologies adopted;
6) Monetary evaluation.

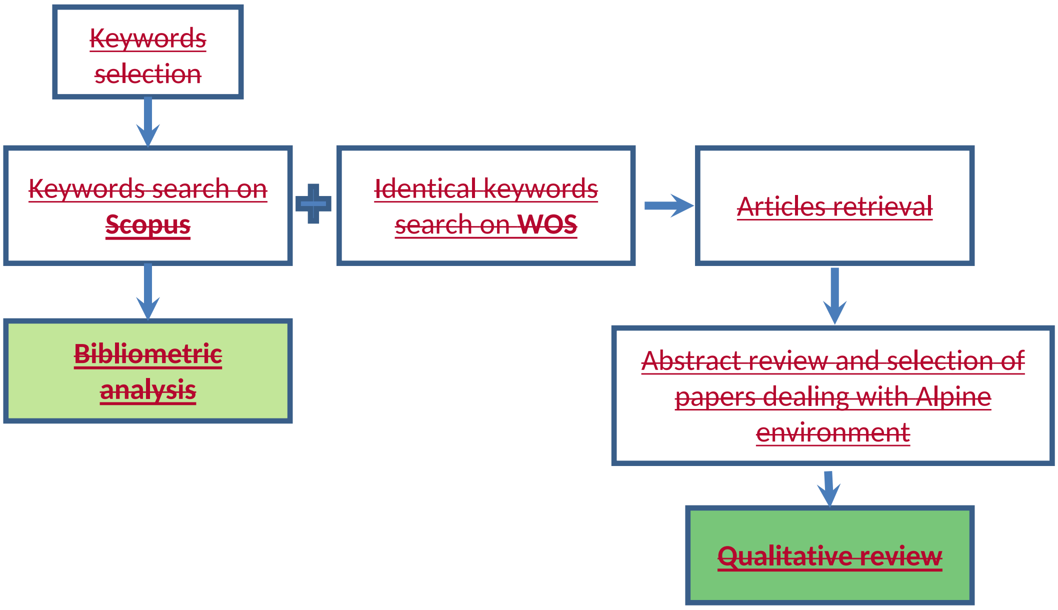

Figure 1 - Workflow used for the review

3. Results and discussion

3.1. Bibliometric analysis

The first search focused on the number of publications indexed on Scopus, concerning risk management related to gravitational hazards. These are the documents which included at least one search term from the natural hazard group and one from the risk management group, in the title, abstract or keywords. The search produced 8,146 results, over the years from 1964 to 2019. The results show a sharp increase in the overall number of publications in this field, rising from less than 50 papers in 1990 to almost 700 per year in 2019 (blue line in Figure 2).

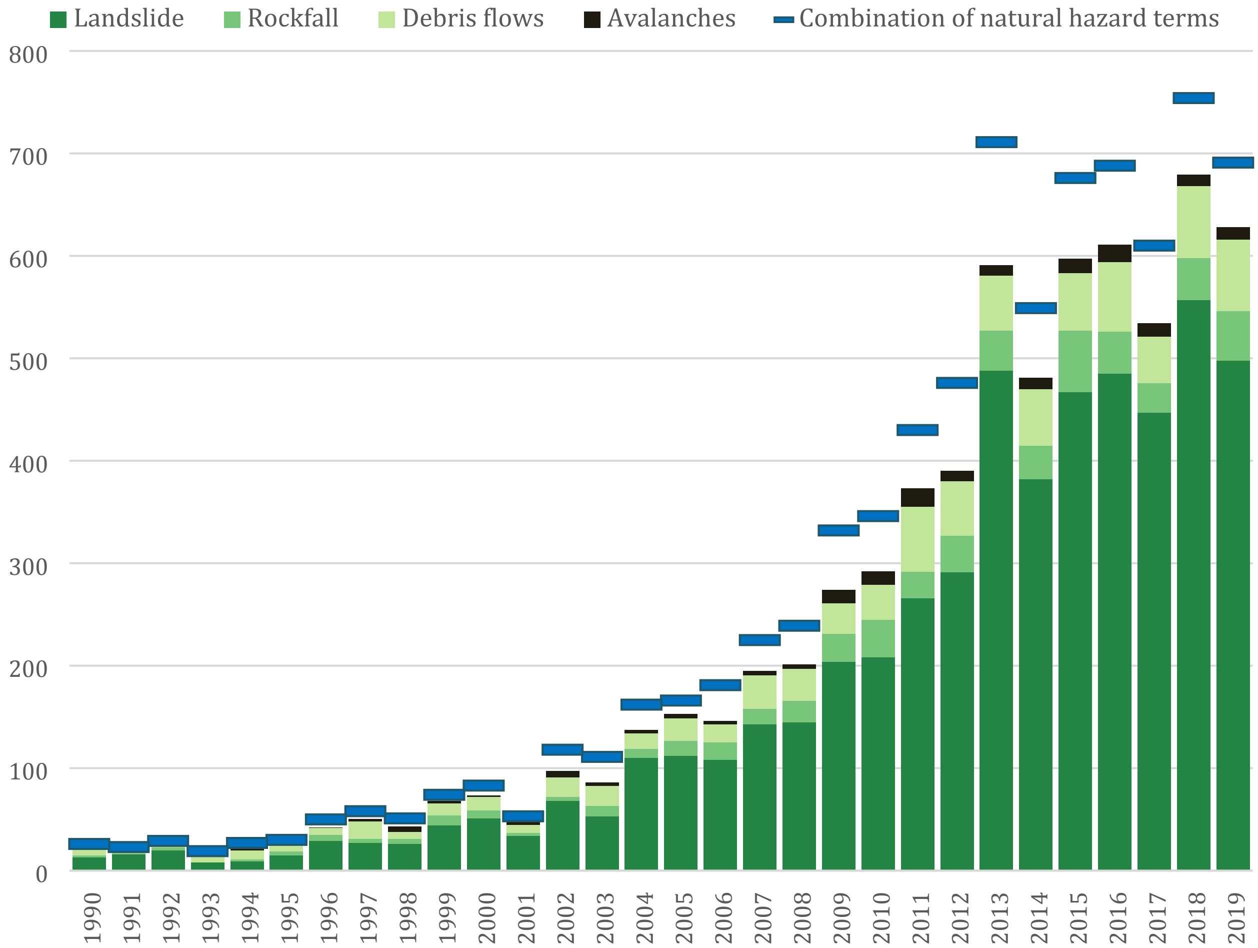

Figure 2. Number of publications indexed on Scopus each year (1990-2019), citing gravitational natural hazards and risk management search terms in their title, abstract or keywords. The different colours of the bar chart show the number of documents in which only one natural hazard is mentioned in the title, abstract and keywords. Some documents refer to more than one natural hazard, therefore the total number of documents indexed in Scopus per year (blue horizontal lines) is higher than the sum of all those mentioning each single natural hazard.

The different colours in the bar chart show the number of documents that cite only one of the selected natural hazards in the title, abstract and keywords. The shades of green represent the publications which include the terms related to landslides (divided into landslides, rockfall, debris flows), the black colour refers to the publications which include the term “avalanche”. Some documents refer to more than one natural hazard in those fields, therefore the total number of documents indexed in Scopus each year (blue horizontal lines) is higher than the sum of all those that mention each single natural hazard. In general, all the gravitational natural hazard search terms showed a considerable increase over time. The most highly cited hazard was landslide, which is also the hazard term that displayed the sharpest increase over the years. The other search terms showed a steady but lower increase. The term “avalanche” (in black) appeared less frequently in combination with terms related to risk management, compared to other gravity-induced natural hazards.

The second step of the bibliometric analysis allowed the selection, among the results of the first search, of the publications which specifically cited the EbS terms (Figure 3, orange line). Only 55 of the total 8,146 publications citing risk management and gravitational natural hazard search terms also included EbS terms. The first document which simultaneously cites terms related to gravity-driven natural hazards, risk management and ecosystem-based solutions, dates to 1991. In the final year analysed, of the 691 publications on risk management, seven also cite green measures. The total number of documents published on Scopus every year has steadily increased over time. Consequently, the research also aimed to compare the growth of the number of publications in this field of interest to that of the overall number of documents indexed in Scopus (see Figure 3). In order to draw this comparison, the ratio between the documents published each year and those published in 2019 was calculated. A ratio equal to one implies that the number of documents published in that given year is the same as the number of documents published in 2019. A ratio higher than one indicates that more documents were published in the given year than in 2019.

In recent years, the publications in this field of interest experienced a sharper increase compared to the overall number of documents published in Scopus. In 1980, only one document mentioning natural hazard and risk management search terms was published, while this number rose to 762 in 2018. The publication trend of papers including ecosystem-based measure terms has shown a less stable growth rate, however, over the last decade, the topic seen a moderate increase: the search query found no documents in 2000, while the number rose to 6, 10 and 7 per year, respectively in 2019, 2018 and 2017.

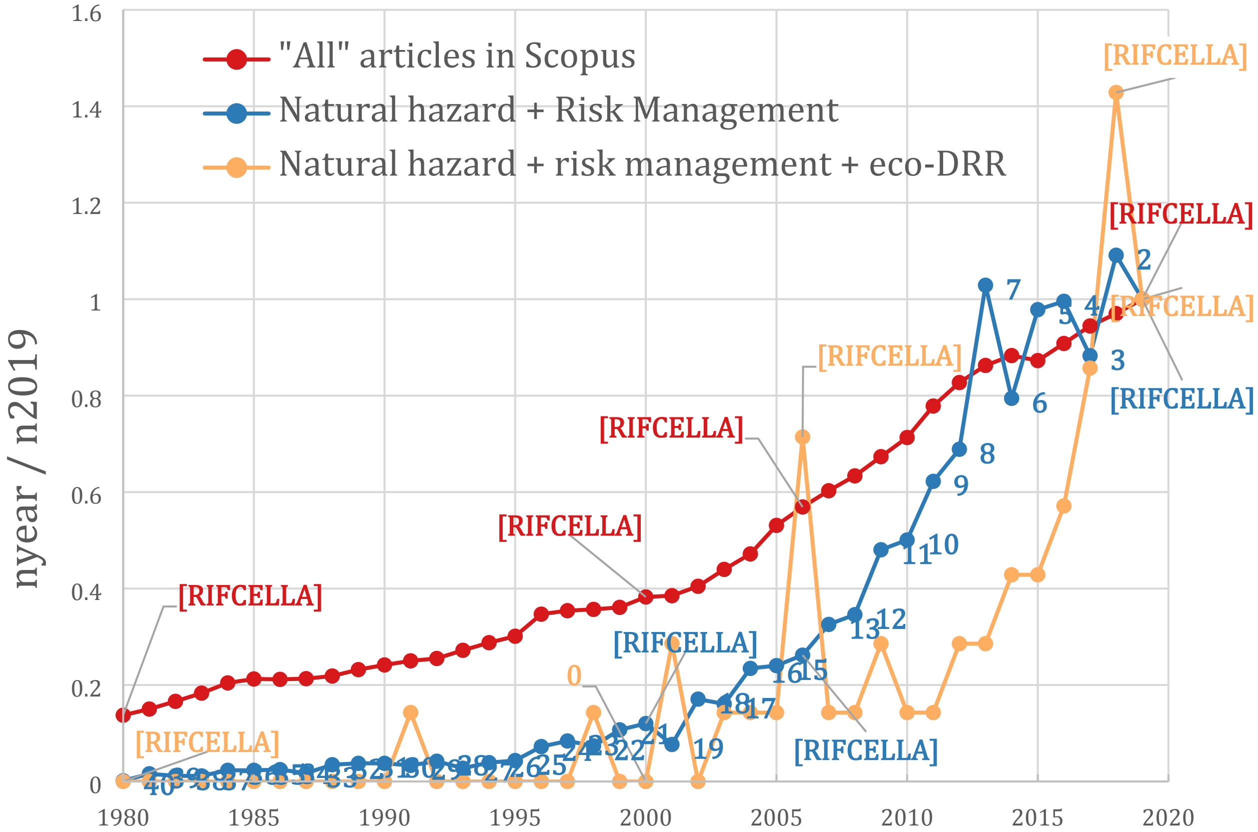

Figure 3. Ratio between the number of documents published in a given year and those published in 2019 2019 "(100" on the Y Axis means that the number of documents published in that year is the same as the number of documents published in 2019. A lower value means that less documents were published in the given year compared to 2019 (i.e. a ratio of 20 means that, the number of documents published in that specific year, equals 20% of the number of documents published in ~~2018~~/2019). The numbers indicated by the arrows show the actual number of documents published in a given year.

3.2. Qualitative review

A further search was performed on WOS using the same keywords, and 8 additional papers were found. From these 63 articles (55 in Scopus plus 8 from WOS), following a review of the abstract and conclusions sections, those concerning the alpine environment were selected and further analysed.

In the resulting papers (Annex 1), two main patterns can be observed: the majority had a classic structure, dealing with a definite hazard and focusing on a specific area. On the contrary, others were more focused on providing a useful framework for decisional purposes and were directed to a wider and more mainstream audience [12,30]. Among these, Accastello et al. [12] developed a conceptual framework to develop strategies for risk management aimed at combining "grey" and "green" infrastructures (e.g., respectively, rock nets and protection forests in rockfall prone gradients) to maximize their protective effect, by exploiting the immediate protection effect of the grey infrastructures and the long term protection and resilience provided by the forest. Whereas, [30] mainly concentrated on stakeholder involvement in risk management, considering Eco-DRR in the SENDAI Framework, an agreement which states the sharing of Disaster Risk Reduction between the state and local stakeholders [31].

3.2.1. Study areas and hazards analysed

The first parameter we analysed was the natural hazard dealt with by the papers. Unlike the global trend of papers concerning this topic (see figure 2), in our selection the main hazards considered were avalanches and rockfall, while only a limited number dealt with landslides (Fig. 5).

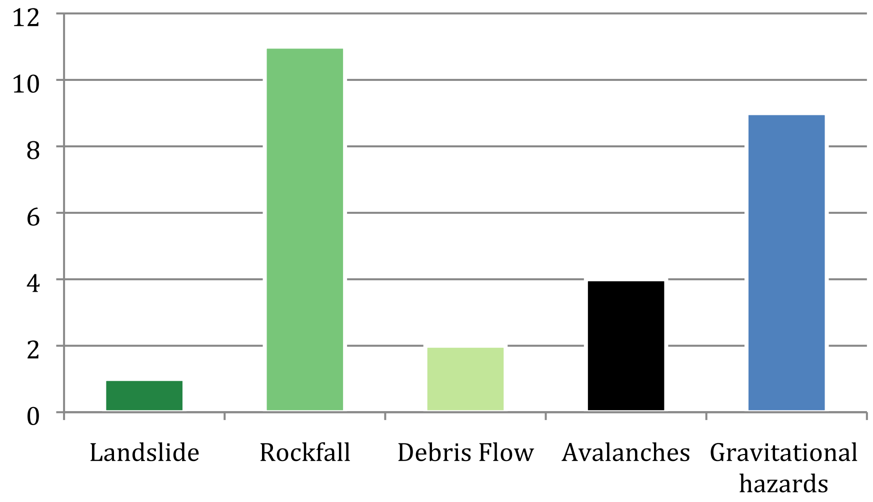

Figure 4 - Number of publications for the different hazards

It was also important to analyse the location of the study areas used in the papers. It is clear from the graph below (Fig. 6), how most of the study cases were carried out in the Swiss and French Alps, while only a few focused on the southern part of the Alps.

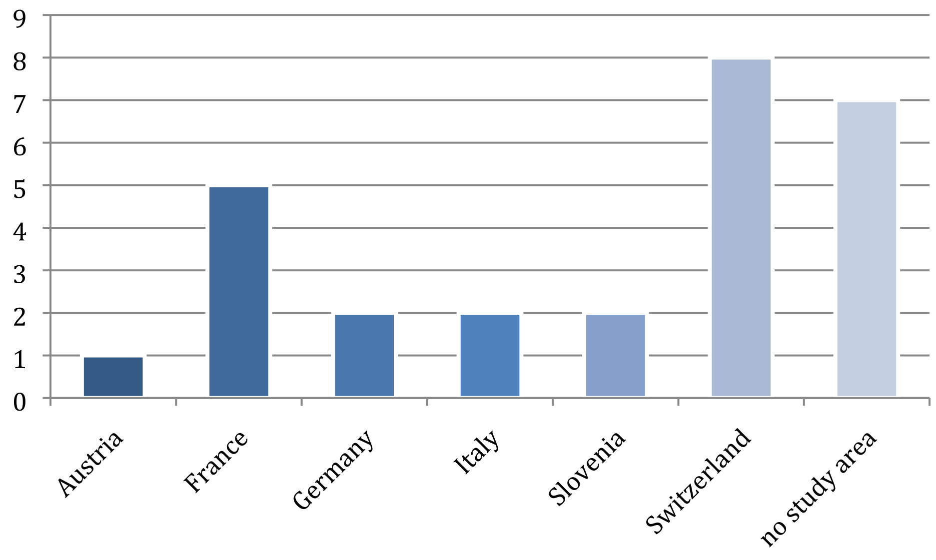

Figure 5 - Study area distribution of the selected articles

Comparing the main hazard featured and the location of the study area, it was interesting to see how studies focusing on different hazards were distributed along the Alps with two main focal areas: Switzerland for avalanches [32–35] and France for rockfall [36–40] (Fig. 7).

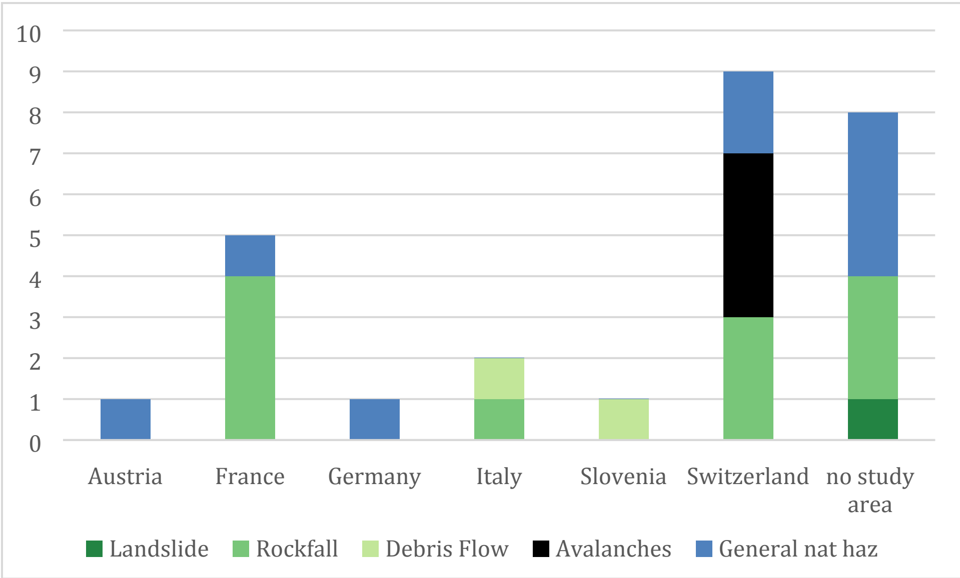

Figure 6 - Study area distribution along the for the different hazards

3.2.2. Forest effectiveness

As mentioned previously, we focused this review on risk management measures in which forests play a predominant role. As a result, in all the papers collected the protective effect of forests was addressed, but in different ways. The common ground in all the articles was the need for appropriate forest management to ensure efficient protective effects against different hazards. In the majority of the studies, the main silvicultural goal, in order to achieve the maximum protection from natural hazards, was an uneven, multi-layered forest stand [21,41,42]. This forest structure was considered to be the most efficient for all of the gravitational hazards considered in this review. Aiming for an uneven-aged forest through silvicultural techniques had the objective of developing a forest structures similar to natural ones, those with the highest resistance and resilience. This objective was stated directly in some of the selected papers, in particular in: [12,20,22,40–43]. In [41], it was also stated that aiming for an uneven and layered forest structure was a best way to imitate natural disturbances, naturally occurring in forest stands.

Concerning the forest structures in [30,32,44] the role of the gaps in the forest cover was addressed, and the maximum dimension of gaps to still ensure an efficient protective effect was evaluated. The issue related to forest gaps was analysed both in terms of avalanches and rockfall. In particular, gaps resulted to be critical in avalanche starting zones, where the forest played a leading role in preventing the detachment of the snowpack [32,33], whereas they played a critical role in the rockfall track zone, as they may allow rocks to fall without obstacles and to thus gain speed [45]. Additionally, the species composition of the stands was analysed. In the papers addressing avalanches [34] as the main hazard, a comparison was made between deciduous and evergreen species, with the latter resulting as the most efficient. This was due to two main reasons: the first was the accumulation of snow on the crown, that allows a wider exposure of this snow to both air and sun, leading to a faster sublimation and in return, a lower snowpack height on the ground. The second reason concerned the stability of the snowpack that, protected by the crown cover, was less subjected to the effect of temperature variations between night and day.

Referring to rockfall, an interesting overview on the different species effectiveness was examined in [38]. The authors compared the different forest stands of the French Alps and discovered that coppices dominated by

Fagus sylvatica and *Quercus sp*. stands were the most effective in rockfall mitigation, followed by pure stands of *Castanea sativa* and *Fagus sylvatica*. The lowest mitigation rates were observed in pure coniferous stands of *Pinus sp.* and *Larix decidua*. This led to the conclusion that shade tolerant species were generally more effective in rockfall hazard reduction. This result was also confirmed by [37], where a comparison between *Pinus nigra* reforestation and broadleaf coppices was made, with the former resulting less effective, due to their even-aged and regular structure, whereas the latter were more efficient, mostly due to the high density of coppice shoots. The role of invasive tree species in rockfall risk reduction was also addressed [46], the case of *Ailanthus altissima* was considered and the results showed an energy reduction capacity similar to that of autochthonous species.

3.2.3. Uncertainties and hazard interaction

In eight papers [12,20,22,32,33,37,47,48] uncertainties that may affect the protective function provided by the forest were considered. These studies focused mainly on fires, pests, animal browsing, windthrow and drought, those being the main elements that could affect said forests and compromise their efficiency. From this perspective, in two papers [41,48] the post disturbance management of direct protection forests was considered, in particular the effect of the disturbance on the protection service was analysed. The role of dead wood in the aftermath of the disturbance (windbreak) was examined, focusing on its protective effect, which proved to be significant in the first years following the disturbance and then gradually decreased over successive years.

Another interesting element analysed in [48] is the cascade effect created by a disturbance on the forest, decreasing its capacity to mitigate other events. In this paper, the effect of avalanches on a direct protection forest against rockfall was analysed. The main problems were caused by the frequency with which avalanches occurred, a high avalanche frequency, aside from affecting the protective effect of that stand, also prevented forest regeneration that would reinstate the function of the stand.

3.2.4. Scenario development

Another parameter we wanted to focus on was the development of scenarios as a way to simulate possible future developments of the study area characteristics. Among the selected publications, three considered land use change scenarios [32,35,47]. All these focused on avalanches and the protective effect of forests to counteract them, both in the release and in the transition areas, and one paper [35] also examined rockfall. Virtual scenarios were created, using Geographic Information System (GIS) based methods, to assess the protective effect of forests against avalanches, comparing the runout of an avalanche on a forested slope to the runout of an avalanche on similar slopes both with a sparse or completely lacking forest cover [32]. Both [32,35] provided useful GIS based frameworks to assess forest effectiveness in different scenarios. Additionally, the role of dead wood on the ground deriving from windthrows was considered and different management options were compared to assess the protective effect of snags and logs left on the ground [47].

3.2.5. Stakeholder involvement

The involvement of stakeholders was chosen as a parameter for the review, given its importance as a driver to convey the results of the research environment to the practitioners and the administrations responsible for risk management. However, in the publications selected through the bibliometric analysis of the Scopus and WOS server, only four addressed this issue [12,21,36,44].
In one paper [21], the authors created a model to evaluate the forest protection from an economic point of view, which laid its foundation in the stakeholder demand for protection: the demand for protection was

assessed in a qualitative way, involving the stakeholders affected by the hazard. The same approach based on the stakeholder demand for protection was also used in [12]. In [44] the authors, talking about the translation of the SENDAI Framework at a European scale, underlined the importance of stakeholder involvement in the risk analysis process and the need to instruct the stakeholders concerning the effectiveness of Eco-DRR solutions, based on successful study cases. [36] also focused on the importance of the knowledge transfer between the researchers and the practitioners and addressed the importance of practical guidelines for forest managers.
Our hypothesis for the lack of publications on this topic is that the layout of the analysed works is of a quite technical nature, showing greater attention to the protection "provision" aspects rather than to those concerning the "demand" for protection, according to a traditional and techno-centric view of ecosystem services and risk management itself, that lacks a more solid social involvement.

3.2.6. Monetary evaluation

Finally, among the selected articles, only three [21,44,49] directly dealt with monetary evaluation. In all the aforementioned papers, the protection effect of the forest was evaluated from an economic point of view. The methods adopted were the replacement cost approach [21,44] and the avoided damages approach [49]. In the replacement cost approach, the protection value of the forest was equal to the cost of the technical structures that would have had to be installed in absence of the analysed forest. On the contrary, in the avoided damages approach, the protective value of the forest corresponded to the damages that would occur in the absence of said forest.

While one paper [44] considered the protection value of the forest against different gravitational hazards, [21,49] focused on the protection provided by the forest against rockfall. In [49] the net present value of both protection forests and technical measures was calculated and the protection provided by the forest resulted to be the most economically convenient, taking into consideration both the costs and the benefits deriving from it. In [44] the approach used was a price analysis carried out using a national pricing list. To evaluate the protective effect of forests from an economic point of view, a replacement cost approach was used, and different scenarios were analysed. Both permanent and wooden structures were considered and the costs due to forest management assessed. Finally, in [21], the authors created a model to evaluate the forest protection against rockfall, harmonised at Alpine level. In this model, as mentioned earlier, the replacement cost approach was adopted and in order to conform the model for use on the entire Alpine Space, the technical measures considered as replacement options were rock nets, whose regulation is standardised at European level by the ETAG027 guidelines.

It is worthy of note how, even though forest management was addressed in several publications [12,20,22,40–43], the cost of the operations was never mentioned, nor was the revenue deriving from those activities. This constituted a challenge in comparing the protection provided by the forest with that supplied by technical structures in terms of the cost-benefit ratio.

4. Conclusions

Nature based solutions have proven to be as effective as other technical measures used for disaster risk reduction. In particular, forests, when correctly managed, can result as being highly effective in preventing and mitigating mass movements in the Alps, also responding to the demand for more resilient solutions to changing hazards driven by climate change. Management guidelines (e.g. [50]) have been published in various countries to help forest consultants and administrations to better manage forests with a protective goal and to strengthen their efficacy. However, even though the potential of protection forests is increasingly acknowledged in the research field, there is still a low response by users to these kinds of measures and their use in risk management is still uncommon, shifting the preference to grey and more instant solutions.

Through the bibliographic analysis conducted on the selected publications, we aimed to highlight the potential role of Eco-DRR and take stock of the knowledge currently available on the topic. Other works have recently been published concerning nature-based solutions against natural hazards. The most recent was by Ruangpan et al. [27], where the topic of hydrogeological hazards was addressed and EbS were considered. Unlike our review, where the study areas are mainly situated in mountain ecosystems, this study primarily dealt with an urban environment. Another interesting review is the one by Moos et al.[6], that dealt with the same natural hazards we considered, but approached the matter from a more quantitative perspective, analysing the impact of the forest in reducing the effects of the hazard. Our review also enabled to highlight some research gaps, i.e. some aspects which few of the reviewed studies have considered. Among these, one of the most relevant is represented by a general lack of stakeholder involvement, as was revealed by the qualitative analysis. A higher involvement of stakeholders might represent the driver for wider recognition, also from practitioners, of the effectiveness of Eco-DRR. Data concerning the effectiveness of Eco-DRR could also be strengthened with the support of thorough economic evaluations, and therefore the comparison of the different protection options. These evaluations, severely lacking at the moment, would also provide a helpful insight for users about the most convenient solutions for managing risk in certain areas.

In conclusion, we believe the present review could represent an important tool to raise awareness of practitioners and researchers of the state-of-the-art of the implementation of ecosystem-based solutions to ensure mitigation of natural hazards in mountainous areas. We believe the present analysis could also foster the application of Eco-DRR concepts in other contexts, especially if characterised by similar environmental conditions, and stimulate future studies in order to fill the research gap, which may currently negatively influence a wider adoption of Eco-DRR across the Alps.

5. Acknowledgments

This research was conducted in the context of the GreenRisk4Alps project. GreenRisk4Alps has been financed by Interreg Alpine Space, one of the 15 transnational cooperation programmes covering the whole of the European Union (EU) in the framework of European Regional policy.

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Annex 1

ID	Study name

1 Accastello et al., 2019: A framework for the integration of nature-based solutions in environmental risk management strategies

2 Accastello et al., 2019: ASFORESEE: A Harmonized Model for Economic Evaluation of Forest Protection against Rockfall

3 Bebi et al., 2001: Assessing structures in mountain forests as a basis for investigating the forests' dynamics and protective function

4 Berger et al., 2004: Mountain Protection Forests against Natural Hazards and Risks: New French Developments by Integrating Forests in Risk Zoning

5 Bigot et al., 2009: Quantifying the protective function of a forest against rockfall for past, present and future scenarios using two modelling approaches

6 Brang et al., 2001: Resistance and elasticity: promising concepts for the management of protection forests in the European Alps

7 Brang et al., 2006: Management of protection forests in the European Alps: an overview

8 Breschan et al., 2018: A topography-informed morphology approach for automatic identification of forest gaps critical to the release of avalanches

9 de Jesus Arce-Mojica, 2019: Nature-based solutions (NbS) for reducing the risk of shallow landslides Where do we stand

10 Dorren et al., 2006: Balancing tradition and technology to sustain rockfall-protection forests in the Alps

11 Dupire et al., 2016: The protective effect of forests against rockfalls across the French Alps: Influence of forest diversity

12 Faivre et al., 2018: Translating the Sendai Framework into action: The EU approach to ecosystem-based disaster risk reduction

13 Fidej et al., 2015: Assessment of the protective function of forests against debris flows in a gorge of the Slovenian Alps

14 Getzner et al., 2017: Gravitational hazards: Valuing the protective function of Alpine forests

15 Michielini et al. 2017: Field investigations of the interaction between debris flows and forest vegetation in two Alpine fans

16 Monnet et al., 2010: Using geomatics and airborne laser scanning for rockfall risk zoning: a case study in the French Alps

17 Moos et al., 2017: Quantifying the effect of forests on frequency and intensity of rockfalls

18 Moos et al., 2018: Ecosystem-based disaster risk reduction in mountains

19 Moos et al., 2018: Integrating the mitigating effect of forests into quantitative rockfall risk analysis – Two case studies in Switzerland

20 Moos et al., 2019: Assessing the effect of invasive tree species on rockfall risk – The case of Ailanthus altissima

21 Moos et al., 2019: Economic valuation of ecosystem-based rockfall risk reduction considering disturbances and comparison to structural measures

22 Sakals et al. 2006: The role of forests in reducing hydrogeomorphic hazards

23 Schonenberger et al., 2005: Effect of timber removal from windthrow slopes on the risk of snow avalanches and rockfall

24 Stokes, 2005: Selecting tree species for use in rockfall-protection forests

25 Teich et al., 2009: Evaluating the benefit of avalanche protection forest with GIS-based risk analyses—A case study in Switzerland

26 Teich et al., 2012: Snow Avalanches in Forested Terrain: Influence of Forest Parameters, Topography, and Avalanche Characteristics on Runout Distance

27 Vacchiano et al., 2015: Effect of avalanche frequency on forest ecosystem services in a 1 spruce-fir mountain forest

Conflict of interest statement

The authors declare that there is NO conflict of interest.