Forest-based solutions for reconciling natural hazard reduction with biodiversity benefits

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Abstract

Nature-based solutions (NbS) offer ways to preserve, restore and manage ecosystems to meet today's societal challenges by combining benefits for society and biodiversity. They incorporate natural features and processes into projects to ensure their sustainable development while investing in the integrity of ecosystems. "Forest-based solutions" (FbS) can be identified as NbS forests that provide both human well-being and biodiversity benefits. In this paper, we intend to consider FbS as solutions that help reconcile natural hazard control with biodiversity benefits, and especially highlight the practices and research needs in this field. FbS in this article correspond specifically to forests used or managed for mitigating natural hazards linked to gravity (rockfalls and avalanches) or to water (floods and drought), while preserving, restoring or managing biodiversity. Firstly, we review the definition and development of FbS applied to natural hazard reduction, while stressing issues concerning the design, implementation, and monitoring of these kinds of actions. Secondly, we point out the need to combine natural hazard control with restoration, preservation and management of ecosystems, by posing novel practice and research questions.

Keywords

Natural risks; rockfalls; avalanches; floods; drought; forest management.

1. From Nature-based solutions to Forest-based solutions

1.1 What are Nature-based solutions?

Nature-based solutions (NbS) are defined as actions using nature to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN French Committee 2019 ; Sowińska-Świerkosz and García, 2022). Conserving biodiversity is a major societal challenge, as it is essential to human development and economic activities. NbS aim to reconcile that challenge with others, such as mitigating and fighting climate change, improving health, water supplies and socio-economic development, or preventing natural risks (Rey et al., 2019; Young et al., 2019; Accastello et al., 2019; Alva, 2022).

The concept of NbS was addressed at the 2009 Conference of the Parties to the United Nations Framework Convention on Climate Change and was included in the Global Program of the International Union for Conservation of Nature (IUCN) in 2013 (Eggermont et al., 2015). Following COP21 in 2015, and the World Conservation Congress of 2016, NbS became internationally recognized for their role in the achievement of sustainable development goals such as good health and well-being, clean water and sanitation, life on land and below water, or climate action.

NbS could take one of three forms, implemented alone or jointly in regional actions (IUCN French Committee 2019): i) the preservation of functional and ecologically sound ecosystems; ii) the improved management of ecosystems for their sustainable use for human activities; and iii) the restoration of degraded ecosystems or the creation of new ones.

NbS is closely related to ecological restoration, ecological engineering or green infrastructure, and places a prime importance on the preservation and conservation of natural processes (Poratelli et al., 2020; Ommer et al., 2022).

1.2 Forest-based solutions and their application to natural hazard reduction

Forests can prevent natural hazards or lower their frequency, magnitude, and/or intensity by reducing onset and/or propagation probabilities, especially in mountainous environments (Moos et al., 2018) or coastal regions (Ahmed et al., 2022). Making these regions inhabitable, these so-called “protective forests” (or “protection forests”) therefore represent an effective solution for Ecosystem-based disaster risk reduction (Eco-DRR; Teich et al., 2022. Nehren et al., 2023). Eco-DRR is the “sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the aim to achieve sustainable and resilient development” (Sudmeier-Rieux et al., 2021). Well-managed ecosystems can act as Eco-DRR measures by influencing one or more of the natural hazard components and by providing additional ecosystem services. The latter are essential to increase the socio-economic resilience and sustain the livelihoods of people and communities. This concept first appeared in 2009 and was defined in 2013. It fits the objectives and principles of managing forest ecosystems in areas for protecting people and assets against natural hazards. It is similar to the long-existing concept of multifunctional mountain forest management (Dorren et al., 2004).

As stated previously, NbS bring together various existing approaches. In particular, Eco-DRR matches NbS if it is implemented to address a major societal challenge while providing benefits for biodiversity (IUCN French Committee 2019). It is then possible to incorporate protective forests as Eco-DRR measures to prevent or reduce natural hazards and risks, thus creating resilient landscapes as the overarching goal (Nehren et al., 2014). Therefore, protective forests may be a specific case of NbS, dedicated to preventing and reducing natural hazards. They could be designed as “Forest-based Solutions” (FbS), defined as “actions using or aiming at establishing forests to preserve sound ecosystems, restore degraded ecosystems (or create new ones) and improve management of ecosystems that address societal challenges, simultaneously providing human well-being and biodiversity benefits”. They must be based on the functioning of forest ecosystems, be applied at relevant spatio-temporal scales according to the societal challenge concerned, reconcile local and global issues without reciprocal prejudice, involve all forestry actors for a transversal governance, and stress the importance of awareness and pedagogy (IUCN French Committee, 2019). Furthermore, this kind of management of protective forests to improve their resilience and protective effects generates larger co-benefits, such as carbon sequestration and aesthetical values, and supports local communities' livelihoods (Renaud et al., 2016).

In this paper, FbS correspond specifically to forests used or managed for mitigating natural hazards linked to gravity (rockfalls and avalanches; de Jesús Arce-Mojica T. et al. 2019; Dupire et al., 2020) or to water (floods and drought; Schanze, 2017; Rey, 2021), while preserving, restoring or managing biodiversity (Figure 1). We do not consider risks on forests such as wildfires, storms and parasite attacks.

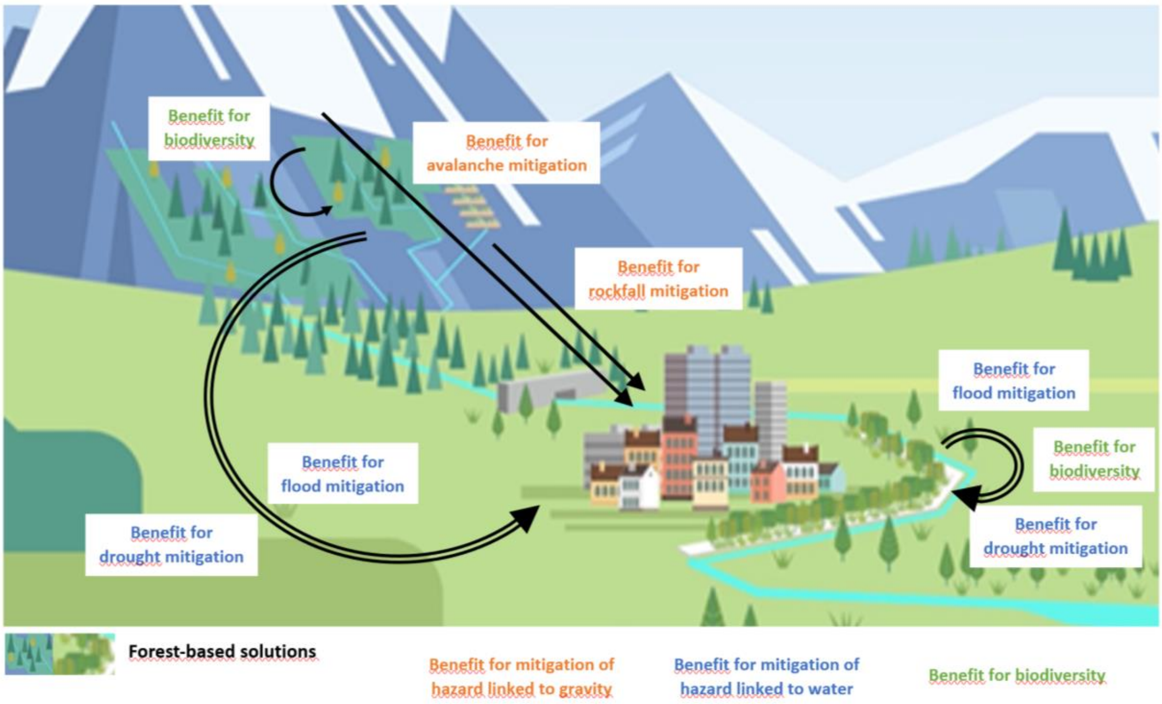

Figure 1: FbS used or managed for mitigating natural hazards linked to gravity (rockfalls and avalanches) and/or to water (floods and drought), while preserving, restoring or managing biodiversity

1.3 History, design and monitoring of Forest-based solutions applied to natural hazard reduction in the Alpine mountains

Historically, “multifunctional forest management”, which combines production, protection and social approaches for forest management, has been deployed on an empirical basis in the Alpine mountainous environment for about 150 years to cope with a wide range of natural hazards including erosion, mountain stream floods with sediment transport, debris flows, snow drifting, snow avalanches and landslides (Vallauri et al., 2002). In France, most of the protection forests planted in the last 150 years were installed in order to reduce erosion and torrential flows (about 90% of the reforested 260 000 ha). Mostly pioneer species were used with a dominance of Pine (*Pinus nigra*, *P. sylvestris*, *P. cembra* and *P. uncinata*) and Larch (*Larix decidua*). However, planting techniques used in the 19th century differ greatly from those used today. For example, for *Pinus nigra* and *P. sylvestris*, the recommendations were to plant bouquet of 3 plants in worked pots spaced 1mx1m (density of ~30000 plants/ha) but nowadays it is 2500 plants/ha with 2x2m spacing. This very high density required numerous silvicultural activities and a huge workforce. Conversely, rockfall protection forests are generally natural reforestation or forests managed with different objectives including protection (Rey and Berger, 2006).

Forests have proved their effectiveness not only at local scales (slope or catchment) but also on large territories where they contributed to reduce natural hazards (Phillips et al., 2013). Over the last 40 to 50 years, protection against mountain hazards have been based on structural countermeasures on one hand and non-structural countermeasures on the other hand. Structural measures mainly consisted in grey solutions installed immediately upstream or upslope of exposed issues and with immediate effectiveness (levees, retention basins) (Tardío-Cerrillo and García-Rodriguez, 2016). Non-structural countermeasures mainly consisted in contingency plans limiting the urbanization in areas exposed to natural risks.

More specifically, forests have historically be used or managed for mitigating natural hazards linked to gravity. For instance, forests act as natural barriers against rockfalls. Trees contribute to stop some of the falling blocks in a way similar to civil engineering structures (i.e. nets or embankments). We called this first effect the “barrier effect” (Figure 2). Moreover, each impact on a tree contributes to a reduction of the energy of the falling rock. Therefore, rock energies observed on forested slopes are generally lower than on open slopes. We called this second effect the « buffer effect » (Dupire et al., 2016a). These two effects increase with the length of the forest along the slope.

Figure 2: Trees contribute to stop some of the falling rocks

Concerning avalanches, the forest cover firstly intercepts both snowfalls (Moeser et al 2015) and solar radiations (Schneebeli and Bebi, 2004), resulting in a thinner and spatially more variable snow pack (snowfall interception) and a lower daily temperature range (solar radiation interception), allowing less weak layer in the snow pack. Secondly, wind speeds observed in forest environments are lower than in open space (Miller, 1964), thus reducing the snow transportation and the formation of wind slabs (McClung, 2003). Thirdly, tree stems act as anchors and stabilize the snow. Forests have been planted in large mountainous areas in order to reduce the triggering of avalanches (Teich et al 2012).

Floods and related erosion are the most important natural hazards in mountainous lands, especially in France and many European countries. In order to mitigate these phenomena, degraded terrains of these lands, mainly in the Alps, were subjected, at the end of the 19th century, to important bioengineering and reforestation works (Figure 3), which proved their efficiency (Phillips et al., 2013). More globally, soil and water bioengineering is largely used for flood mitigation and erosion control, and is recognized as NbS (Rey et al., 2019; Preti et al., 2022). The use of nature can allow an optimization of ecosystem services, in particular natural hazard control, in a more efficient way than the more traditional methods of civil engineering and grey infrastructures (Tardio and Mickovski, 2023). Particularly, the control of these natural hazards requires adapted management of vegetation and especially forests (Vallauri et al., 2002; Bresci and Preti, 2010). More than a hundred years after the first plantations, the sustainability of these forests, threatened by climate changes, has been questioned. It was necessary to find a way to renew the existing forest cover, while facing the current climate, ecological and financial challenges. Scientists thus conducted researches aimed at understanding the links between vegetation, erosion and floods, as well as the impact of regeneration cuts in forests on these processes (Vallauri et al., 2002; Rey and Berger, 2006).

Figure 3: Monospecific planted forest for flood and erosion control in the French Southern Alps

Besides, FbS favors drought reduction, allowing an increase of water infiltration and the recharge of groundwater (Le Coent et al., 2021). Some “natural water retention measures” help to slow down waterflow and increase infiltration of water through changes in practices, including silvicultural practices. In urban water management, patches of trees called “rain gardens” and “rain trees” allow water to infiltrate into the soil, thus facilitating groundwater recharge (Ramirez-Agudelo, 2020; Boano et al., 2020; Simperler et al., 2020; Hérivaux and Le Coent, 2021).

2. Novel practice and research questions for reconciling natural hazard reduction with biodiversity benefits

For a long time, forest managers and scientists have proposed some engineering tools suitable for improving the management of protective forests. Research has been requested to lower the costs and improve the naturality of the final stands, in a "minimal tendings" scope, using the natural processes to minimize the artificial interventions (Rey and Berger, 2006). The concept of FbS should be explored more deeply by scientists on this aspect, notably in the design and assessment of management approaches and diversification practices (Nesshöver et al., 2017). Firstly, a central question is to know if more biodiversity in forests rhymes with more reduction of natural hazards. Secondly, research is questioned concerning upscaling and transposition of FbS from the scales of tree to slope or to catchment.

2.1. Can biodiversity increase natural hazard control?

Multifunctional forest management should be developed on a more scientific basis with consideration of ecosystems services and restoration, preservation and management of biodiversity. Alternatives in terms of soft management and green techniques replacing civil engineering structures have already been tested considering their effectiveness and cost/benefit ratio. But, considering biodiversity using FbS for mitigating natural hazards should be increased. This will allow techniques to be better integrated in global protection strategies and transposed to other sites and at a larger scale (Sahani et al., 2019).

Unlike for other natural hazards, protection forests against rockfalls are generally not planted but rather of natural origin or the result of agricultural abandonment. Therefore, the identification of forest stands able to provide efficient rockfall control has been specifically investigated. Forest diversity at large, i.e. including both structural heterogeneity and tree species, influences the forest's ability to reduce rockfall hazard. Thus, the more diverse the forest, the more efficient it will be in reducing rockfalls (Dupire et al 2016b) and resilient to face human and natural disturbances (Figure 4).

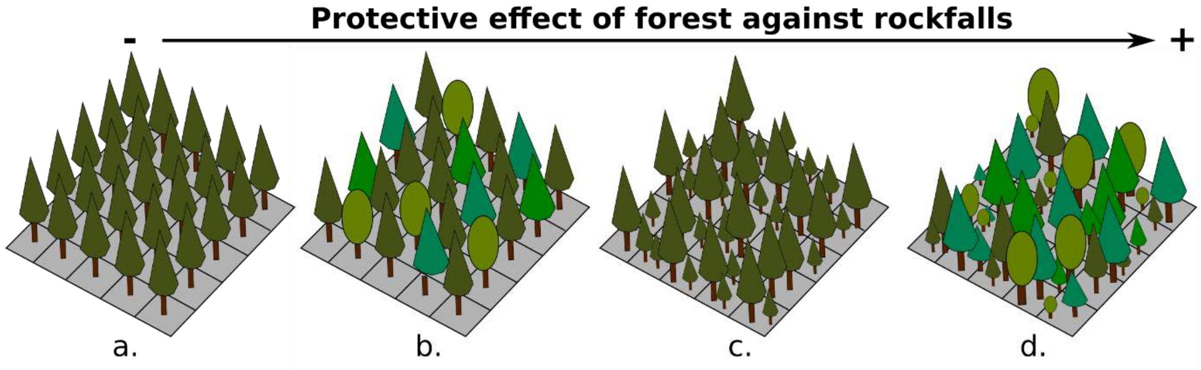

Figure 4: The protective effect on rockfalls increases with forest diversity including both diversity in forest structure and species composition (adapted from Dupire et al. 2016b).a. Monospecific and even-aged plantation. b. Mixed even-aged forest, c. monospecific unevenaged forest, d. unevenaged forest with multiple species.

This is a supplementary step in understanding the role of forest diversity in their protective effect on rockfalls. Nevertheless, a better understanding of the mechanical behavior of standing trees towards rockfalls, at the tree scale, remains necessary. What are the intra- vs inter-species differences in mechanical capabilities of forest stands? Recent publications show that the most important parameters used for quantifying the protective effect of forests against rockfalls are (1) the area occupied by the trees (i.e. the basal area which drive the probability to hit a tree), (2) the size of trees (i.e. diameter which defines their capacity to reduce energy) and (3) the length of forest cover along the slope. Although the species effect is secondary it is still not well known. It appears also important to better understanding the mechanical capacities of healthy trees and shrubs affected by disturbances (drought, fire, pathogens). Future works should therefore combine in-depth studies of the mechanicals properties of standing trees and their functional ecology. The study of mechanical characteristics of standing trees may provide a sort of "generalist" trait linked to the capability of protection at the tree scale. Knowing how this trait evolves following disturbances is also relevant in the current context of climate change. The final objective would be to identify trade-offs between an efficient protection at a specific time and a sustainable protection over time even after disturbances.

The significance of NbS in reducing floods has also been largely studied (i.e., Huang et al., 2020; Raska et al., 2022; Chui et al., 2022). It has been shown that restoration of nature globally increases the reduction of flood hazards, especially using ecological engineering and mainly for actions at the catchment scale (Rey, 2021). If the advantage of using NbS for improving biodiversity is often mentioned (Boelee et al., 2017; Seddon et al., 2020), the use of biodiversity for increasing the effectiveness of flood control measures is as important. Thus the use of forests and the significance of their species diversity for mitigating floods should be regarded (Vallauri et al., 2002). Consequently, further research is needed to increase knowledge and expertise in this field.

To summarize, several questions are raised today around FbS by water professionals, such as, in order of priority: what is the effectiveness (and risks) of different FbS (i.e., with different species composition) in different situations? How to evaluate them? What long-term monitoring is needed before, during and after the implementation of FBS for adaptive management, in connection with their operation and maintenance? Besides, other questions arise concerning social, economic and political aspects, respectively: what does the implementation of FbS imply in terms of skills (and therefore training needs), business lines, organisations and governance? What socio-economic approach facilitates the implementation of FbS? What ownership by local authorities (socio-technical aspects), citizens and users, and what about the coherence of policies and public actions related to risk management?

2.2. Upscaling and transposition of FbS

Climate and societal changes are likely to sustainably and negatively affect forest ecosystems in the coming decades. These effects are materialized on the one hand by the emergence or increase of natural disturbances (forest fire, drought, storm) and on the other hand by changes in the structure and/or composition of forest stands. Understanding and anticipating these effects in order to prevent adverse consequences for the protection of people and human assets from natural hazards is therefore a major challenge for decades to come.

We could also work on the possible conflicts between the development of FbS and the preservation of ecosystems. For instance, effective FbS may sometimes lead to the reduction of biodiversity, or increase the effects of disturbances such as wildfires. To this end, the Integrated risk management (IRM) concept should be reinforced to deal with multiple risks and a better consideration in protection strategies of all socio-economic issues present in exposed territories (Teich et al., 2022). This includes for instance transport infrastructures, economical activities and generally speaking all elements contributing to the development of these territories. It should emphasize the role played by local authorities and citizens, keeping in mind that these latter often lack proper information about risks, especially in urban areas. It should also explore alternative strategies of development contributing to the resilience of territories facing natural risks. Inter-dependence of territories should also be considered at several scales. Considering all these aspects is required for a proper and effective integration of FbS in protection strategies and will contribute to their acceptance.

This also includes proper assessment of FbS services and their consequences in terms of IRM and its specific governance (Nesshover et al., 2017). This involves the consideration of benefits and limits based on scenarios including features of considered territories (type of hazard, stakes present, trajectories of development of considered territories, local governance) and climate (altitude, drought). Indeed, how to evaluate the proper position of FbS in a global strategy of protection which inevitably has to consider protection by technical means, but also all aspects of the risk circle from preparedness to recovery? We can contribute to analyze existing or potential protection strategies by developing tools based on multi criteria decision analysis. Also, robust information, data and models about how different types of FbS contribute to specific benefits and risks in different landscape settings will be essential to inform decision analysis and making. A particular feature of mountain territories is the presence of several risks on the same territories. We could work on the optimization of FbS solutions under the constraint of possibly conflicting protection goals. Capitalizing on the long experience gained in Alpine environment, we could develop indicators on the capabilities and limits of FbS to cope with natural risks reduction while preserving, restoring or managing ecosystems and biodiversity (Shah et al., 2020).

3. Conclusion

For a long time, many research teams are active in several FbS initiatives, and more research is still needed to increase knowledge and expertise in this field. Investigations to be carried out, a source of both disciplinary and interdisciplinary research, combine approaches in forest sciences, ecology, geosciences and social sciences. Cross-disciplinary, multi-stakeholder and innovative in the multiple benefits they offer, FbS can be applied to aquatic, terrestrial, and interface environments. All this should contribute to the establishment of guidelines and recommendations concerning the proper evaluation of existing FbS, the assessment of proper FbS to be applied in various contexts, the benefits and limits to be expected, and the appropriate way to better include FbS in global protection strategies considering features of considered territories and possible evolutions of their environment, including climate.

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