GLOBAL CHANGE IMPACTS ON AVALANCHE PROTECTIVE FORESTS—CURRENT KNOWLEDGE AND FUTURE RESEARCH DIRECTIONS

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ABSTRACT: Protective forests provide an indispensable ecosystem service by protecting people and infrastructure against natural hazards and, therefore, serve a vital role in managing associated risks. Forests growing in avalanche terrain can inhibit avalanche formation by stabilizing the snowpack and significantly decelerate or stop small to medium size avalanches that have released within forests or closely above the treeline. However, forests are increasingly affected by global change, including climate change, more frequent and severe natural disturbances, and shifts in land use, affecting the long-term and sustainable provision of their protective services. To improve our understanding of the various impacts that global change has on avalanche protective forests, we summarized the current knowledge based on a systematic literature review following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) method. This resulted in 36 peer-reviewed, English publications, which specifically addressed changes in forests' protective effects against snow avalanches under global change. The geographic distribution of the studies' locations reflects the long tradition and institutional embedding of protective forest management in the European Alps. Overall, most of the reviewed studies report at least partly negative impacts of global change on the protective effects of forests against snow avalanches, especially under exacerbating climate change scenarios. A decline in forest growing stock due to more frequent and severe disturbances, drought-related mortality or growth decrease, as well as due to land-use change or intensive management is expected to reduce the protective effect in the long-term. However, climate change-related growth increases at high elevations, re-/afforestation as well as post-disturbance legacies can positively affect avalanche protective forests. Most of the reviewed studies were case studies using indicators of forest structure, while quantitative hazard and risk assessments were less common. Studies often used forest simulation models or process-based avalanche models, but never combined the two. More empirical studies and monitoring efforts, consistent indicators across different case studies as well as modeling approaches linking forest structure to hazard and risk are needed for a better understanding of changes in avalanche protective forests to support a pro-active and sustainable management of these extremely valuable Nature-based Solutions under global change.

KEYWORDS: protective forest, Nature-based Solution, snow avalanche, climate change, natural disturbance, land-use change

1. INTRODUCTION

Forests play a crucial role in mitigating snow avalanche risk in mountain areas by inhibiting avalanche formation and release or reducing the runout distance of small and medium avalanches that release in forests or shortly above the treeline (Moos et al., 2018). These avalanche protective forests have the primary function of mitigating avalanche risk by reducing the probability and impact of avalanches for people, settlements and infrastructure (Brang et al., 2001). They are a Nature-based Solution for Disaster Risk Reduction in mountain areas that offers cost-effective and sustainable protection, while also providing additional environmental benefits and ecosystem services, unlike expensive technical protection measures (e.g., Getzner et al., 2017; Olschewski et al., 2012).

However, global change, such as climate change and human activities, is affecting these forest ecosystems (e.g., Albrich et al., 2020), raising questions about the long-term and sustainable provision of protection from avalanches and other natural hazards. Rising temperatures, shifting tree species distributions and disturbance regimes, as well as land-use changes and forest management interventions, are altering forest ex-

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tent, composition and structure, potentially altering their protective effect (Moos et al., 2023). These changes pose significant challenges for the sustainable management of protective forests in mountain regions (Thrippleton et al., 2023).

To improve our understanding of the various impacts of global change on avalanche protection by forests, we conducted a systematic literature review which synthesizes research on how certain aspects of global change affect the protective effects of forests against snow avalanches. This review is based on our previous review article that only accounted for studies published until 4 August 2022, and also included other natural hazard processes in mountain areas such as rockfall, shallow landsides, torrential flooding, and debris flows (Moos et al., 2023). For this review, we extended the literature search through July 2024.

Focusing on climate-induced and anthropogenic forest changes as well as large-scale natural disturbances and their implications for the protective effect of forests against snow avalanches, we provide an overview of the existing literature, including the geographical distribution of the studies as well as the methods applied to detect the changes in forests' protective effect, and discuss the interactions of different global change impacts. Our findings highlight critical knowledge gaps and suggest future research directions to improve forest management strategies in the face of ongoing global change.

2. METHODS

2.1 Literature search

We conducted a systematic literature review using the PRISMA method (Page et al., 2021) to ensure transparency. The Web of Science database was searched using terms related to "protective forest", "global change", and "protective service" (Table 1), focusing on titles, keywords, and abstracts. To broaden our scope, we also included results from Google Scholar by searching terms like "avalanche protective forest" and "climate change" as well as "impact of global change on avalanche protective forests". The entire search yielded 617 publications as of July 31, 2024.

Table 1: Literature search terms per search category.

Category	**Search terms**
Protective forest	forest* OR "protection forest" OR "protective forest" OR "Eco-DRR" OR "Nature-based Solution"
Global change	"climate change" OR "global change" OR change OR drought OR disturbance OR future OR evolution OR "forest dynamics" OR "ecosystem dynamics" OR "dynamic" OR development*
Protective service	avalanche OR "snow avalanche" OR "risk reduction" OR "protective effect" OR "protection effect" OR "protective function" OR "protection function" OR "protective capacity" OR "protective service" OR "protection service"

We further included two relevant publications known to us that were not captured in the initial search (Kupferschmid Albisetti et al., 2003; McClung, 2001) and excluded our previously published review article (Moos et al., 2023) for the analysis. We then screened titles and abstracts to ensure thematic relevance, focusing solely on studies addressing changes in forests' ability to protect against snow avalanches in mountain areas under global change (Table 2). Non-peer-reviewed documents, non-English publications, and unrelated studies were excluded, resulting in 36 relevant publications for detailed review.

Table 2: Selection criteria for the detailed review.

Criteria	**Specifications**
Avalanche hazard	Publications without a clear link to snow avalanches were excluded (e.g., publications that mention snow avalanches only as an example for natural hazards in mountain areas).
Global change impacts	Studies addressing changes in protective effects related to climate change (e.g., increasing drought or altering natural disturbances) or anthropogenic changes (e.g., management interventions, land-use change).
Protective effect	Publications were included only if a clear link between the protective effect against avalanches and forest changes related to global change impacts was established. Papers focusing on the general role of forests in climate change mitigation were excluded.
Publication type	Peer-reviewed articles, books, book chapters, and conference papers in English; exclusion of "gray literature" and preprints.

2.2 *Literature assessment and analysis*

In a systematic review of the selected publications, we documented key details such as the study's location and elevation range. We categorized the studies based on the following three main aspects of global change impacts:

- Climate-induced forest change: Alterations in forest composition, structure, and/or extent due to changing air temperature and precipitation (e.g., changes in growth conditions, mortality rates, or treeline shifts)
- Large-scale natural disturbances: Changes following disturbances caused by, e.g., forest fires, windthrow, pathogens or insect infestations
- Anthropogenic forest change: Human-driven changes such as land-use change, de-/afforestation, or management interventions

We analyzed if these factors influenced (1) forest composition, (2) structure, and/or (3) extent, and subsequently affected their protective effect against snow avalanches. Changes in protective effects were classified into five categories: increase, decrease, no change, scenario-dependent, or inconclusive. If multiple scenarios (e.g., climate change or management scenarios) were considered, we assessed each one individually.

We also examined the methodologies used to evaluate changes in protective effects, categorizing them as field-based/empirical, statistical modeling, process-based/numerical modeling, experimental, expert estimation, participatory studies, or reviews. The variables used to characterize the change in protective effects were classified as qualitative or quantitative, and we noted whether they were directly related to avalanche hazard or risk (e.g., effect on avalanche frequency, intensity, and/or risk) or indirectly through changes in forest structure (e.g., protective forest indices).

Finally, we analyzed the impacts of the selected global change aspects in detail, assessing how avalanche protective forests at various elevations were affected by climate change, natural disturbances, and/ or management practices.

3. RESULTS

3.1 *Overview*

The first publication on global change impacts on protective effects of forests against snow avalanches appeared in 2001 (Figure 1). The number of studies published each year fluctuated between zero and three until a first peak in 2017 with six publications. A second peak occurred in 2020 with four publications, after which the number of new publications remained constant. Throughout this period, studies consistently addressed the impacts of anthropogenic forest change and natural disturbances on forests' protective effects, while research on climate-induced changes began in 2009 and increased after 2013.

Overall, most studies addressed anthropogenic impacts (69% of all studies), followed by natural disturbances (50%), and climate-induced changes (33%), with nearly half of the studies examining combined or interacting impacts (47%).

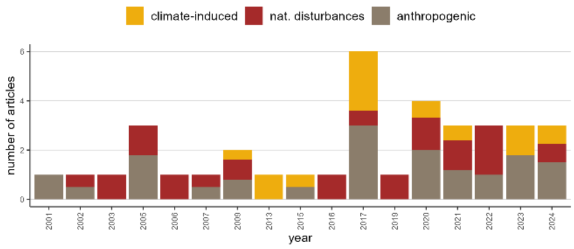

Figure 1: Number of publications per year divided by the addressed global change impact categories (total number of publications = 36; multiple categories per publication possible).

Most research was conducted in the European Alps, i.e., 14 studies in Switzerland, 5 in Austria, 4 in France, and 2 in Italy, reflecting the region's long tradition of managing protective forests. One study was from the Cantabrian Mountains in Spain (García-Hernández et al., 2017), and one from the Tatra Mountains in Poland (Gądek et al., 2017). Six publications, including three review articles, contained studies from multiple mountain ranges, countries and/or continents. Only three studies were conducted with data collected outside of Europe, two in Canada (Germain et al., 2005; McClung, 2001) and one in the USA (Teich et al., 2019).

Most studies employed quantitative methods (81%), with almost half of all studies utilizing process-based/numerical modeling to assess global change impacts on protective effects of forests against snow avalanches (Figures 2 and 3). Commonly used models were either avalanche dynamics models such as RAMMS (e.g., Caduff et al., 2022; Gądek et al., 2017) or forest simulation models such as PICUS (e.g., Irauschek et al., 2017; Maroschek et al., 2015), MASSIMO (Mathys et al., 2021), or ForClim (e.g., Elkin et al., 2013; Hillebrand et al., 2023); however, they were never combined. Field-based or empirical data were used in 47% of all studies and four studies applied statistical modeling. Experiments, expert estimations or literature reviews were applied in 25% of the analyzed publications. However, multiple methods were often combined.

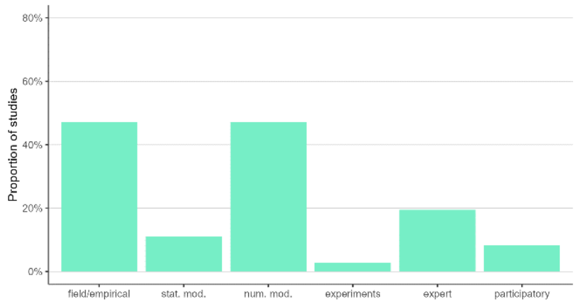

Figure 2: Methods used to assess the change in the protective effect of forests (total number of studies = 36; multiple methods per study possible).

Fifty percent of the studies focused exclusively on the protective effect of forests against snow avalanches, while the remaining studies examined multiple natural hazards (50%) and/or ecosystem services: 28% on wood production, 22% on biodiversity, and 17% on carbon sequestration.

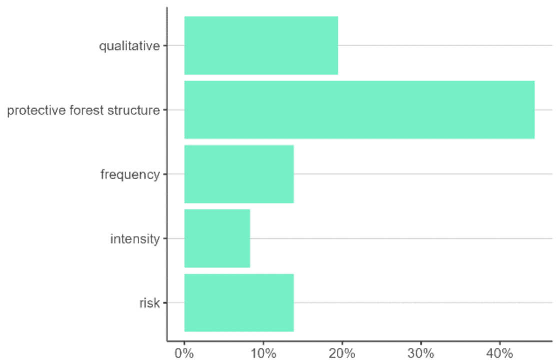

Figure 3: Proportion of publications that assessed the impacts of global change on the protective effect qualitatively ("qualitative") or quantitatively based on the protective forest structure or a component of natural hazard risk (i.e., frequency, intensity/magnitude, or risk).

3.2 *Climate-induced forest change*

One-third of the publications (n=12) examined how climate-induced changes in forests impact their protective effect against snow avalanches. Most of these studies examined shifts in forest composition or structure, with only two addressing changes in climate-driven forest extent at the treeline.

Ten of these studies were "predictive", assessing potential future forest changes under different climate scenarios. Nine of the "predictive" studies employed forest simulation models. To assess changes in the protective effect, these studies used model outputs to calculate dimensionless protective forest indices such as the avalanche protection index API (Cordonnier et al., 2014; applied in seven of the nine forest modeling studies), which quantifies the difference of the modeled forest structure to a targeted structure representing maximum protection, rather than directly quantifying forest effects on the avalanche hazard (Figure 3).

Several of these studies agree that rising air temperatures enhance forest growth and thereby benefit the protective effect of forests at higher elevations above 1500 m a.s.l. (e.g., Elkin et al., 2013; Irauschek et al., 2017a, b; Mina et al., 2017; Thrippleton et al., 2020, 2023). In contrast, more frequent and severe droughts could diminish the protective effect at elevations below 1000 m a.s.l. due to increased mortality and reduced growth (e.g., Elkin et al., 2013; Hillebrand et al., 2023; Mina et al., 2017). In-between, climate change impacts vary depending on local conditions and the specific climate scenario considered. Moreover, Maroschek et al. (2015), Irauschek et al. (2017b) and Thrippleton et al. (2020, 2023) emphasize the counterbalancing effects of climate change on tree growth (enhancing protection) and increasing natural disturbances (reducing protection). In addition, few studies concluded that silvicultural interventions may have greater influence on the protective effect against snow avalanches than climate-induced changes in forest structure (e.g., Irauschek et al., 2017a; Mina et al., 2017).

Konic et al. (2024) used forest inventory data to predict and analyze changes in protective effects against snow avalanches under different climate scenarios and adaptation strategies through replacing current tree species by more suitable native and non-native trees. Their results suggest that it is important to replace broadleaf trees with other broadleaf species, and coniferous trees with other conifers. This approach could increase protective effects, rather than simply focusing on any tree species that could be suitable in a future climate.

Only two studies were based on actual observations of how past and current climate change has affected the protective effects of forests. Gądek et al. (2017) found that the climate change-driven upward expansion of the treeline into large avalanche tracks had no influence on runout length in a case study area in the Tatra Mountains. Bebi et al. (2009) related inventory data on forest cover change in the Swiss Alps between the periods 1979/1985 and 1992/1997 to topographical variables and potential avalanche process areas. They concluded that a further increase in avalanche protective effect can be expected but not necessarily in forests located on very steep slopes.

3.3 Large-scale natural disturbances

Of the 36 reviewed publications, 18 addressed how changes in forest structure caused by natural forest disturbances, such as windthrow, bark beetle outbreaks, and forest fires, impact the protective effect of forests against snow avalanches (Figure 4). Windthrow was the most frequently studied disturbance (11 studies), followed by bark beetle outbreaks (7 studies), and forest fires (4 studies). These disturbances often reduce the protective effect of forests for several years to decades, which depends on their severity such as the level of tree mortality or the degree of change in forest structure (Oven et al., 2020; Vacchiano et al., 2016); however, disturbance severity was not consistently quantified in the reviewed studies.

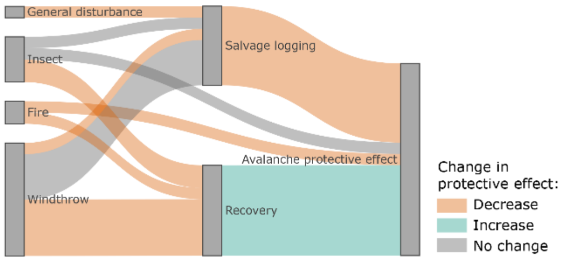

Figure 4: Number of studies addressing the effects of different types of natural disturbances (left) on the protective effect of forests against avalanches, either directly, or mediated by the processes of salvage logging or recovery. For example, some studies indicating no change of protective effect after the disturbance itself, but a decrease after salvage logging. The width of the connection indicates the number of studies addressing the specific link.

All studies based on empirical data concluded that post-disturbance management decisions significantly influenced the remaining protective effect of forests against snow avalanches. That is, retaining standing and lying deadwood in wind and bark beetle-disturbed forests contributed to maintaining and recovering their protective effect, especially during the first 15 years after the disturbance (e.g., Baggio et al., 2022; Caduff et al., 2022; Frey & Thee, 2002; Kupferschmid Albisetti et al., 2003; Schönenberger et al., 2005). In contrast, salvage logging often further impairs the protective effect of forests (Leverkus et al., 2021; Teich et al., 2019; Wohlgemuth et al., 2017).

Stritih et al. (2024) showed that over 40% of forests in the European Alps that were disturbed between 1986 and 2020 maintained their protective effect, and that 61% of forests were likely to either maintain or recover it within 30 years after wind and bark beetle disturbance, highlighting the key role of residual living or dead trees. Caduff et al. (2022) used remote sensing data and avalanche simulations to assess disturbed forests' protective effect following windthrow and bark beetle outbreaks. They found the lowest protective effect approximately 10-15 years after disturbance, coinciding with the decay of deadwood. However, approximately 25 to 50 years after windthrow events in three study sites in Switzerland, the protective effect was still considered insufficient due to the slow speed of natural regeneration (Rammig et al., 2006, 2007; Wohlgemuth et al., 2017).

3.4 Anthropogenic forest change

The impacts of anthropogenic changes on forests and their protective effects against snow avalanches were addressed in 18 studies[1]. They were linked to land-use change (deforestation, including clear-cuts; afforestation of previously non-forested areas; and reforestation, often following the abandonment of pastures), management interventions (thinning, regeneration cuts, and afforestation in forested areas), and other activities (e.g., forest grazing or reduced/no management activities), and often studied in combination with climate change (8 publications).

Most studies on anthropogenic forest changes addressed regeneration cuts (n=7). The second most studied factor was "reduced/no management" (n=6), followed by deforestation, including large-scale and partial clear-cuts (n=5), reforestation (n=4), afforestation (n=3), and thinning (n=2). Two studies examined specific activities like forest grazing (Mayer and Stöckli, 2005) or the introduction of non-native tree species (Konic et al., 2024).

Several studies utilized forest simulation modeling approaches to investigate the effects of anthropogenic forest changes on the protective effect against snow avalanches, both with and without interaction with varying climate scenarios (Hillebrand et al., 2023; Irauschek et al., 2017a, b; Maroschek et al., 2015; Mathys et al., 2021; Mina et al., 2017; Thrippleton et al., 2020, 2023).

Regeneration cuts and thinning had varying impacts on the protective effect of forests under different climate scenarios. Positive effects of these interventions were often reported under no climate change, with negative effects becoming more common under moderate to strong climate change scenarios (e.g., Maroschek et al., 2015; Thrippleton et al., 2020).

Nevertheless, even under strong climate change scenarios, several studies highlighted a relatively

[1] Publications on salvage logging following disturbances were excluded from this section, as they are covered in Section 3.3.

positive influence of clear-cuts (Irauschek et al. 2017b), regeneration cuts (Irauschek et al. 2017a, b; Mathys et al. 2021), and thinning (Mathys et al. 2021) on the protective effect of forests, underscoring the complexity of interactions between climate change and direct anthropogenic influences on protective forests.

Without considering climate change, "no management" generally enhanced protection against snow avalanches by forests. However, under moderate to strong climate change scenarios, negative effects of "no management" were observed (Irauschek et al. 2017b; Thrippleton et al. 2020; Konic et al. 2024).

Deforestation was generally found to diminish the protective benefits provided by forests (García-Hernández et al., 2017; Germain et al., 2005; McClung, 2001; Teich and Bebi, 2009); however, one study noted a positive impact of clearcuts (concentrated on 5000 m² strips, followed by planting) on the protective effect against snow avalanches, particularly under no to moderate climate scenarios (Irauschek et al., 2017b).

Re- and afforestations generally enhanced avalanche protection by forests (García-Hernández et al., 2017; Mainieri et al., 2020). However, their protective effect highly depends on management decision following the establishment of new protective forests such as sustainable grazing practices (Grätz et al., 2024), or where reforestation takes place (Zgheib et al., 2022a, b). For example, Zgheib et al. (2020) highlighted that incomplete reforestation in avalanche paths following land abandonment did not reduce the avalanche risk to settlements, particularly when combined with urban expansion into avalanche prone areas.

4. DISCUSSION AND CONCLUSIONS

This review highlights the complexity of global change impacts on the protective effect of forests against snow avalanches. Factors like more frequent and severe disturbances, drought-related tree mortality, and deforestation generally reduce the protective effects of forests. In contrast, climate-driven tree growth at high elevations, afforestation and reforestation following land abandonment as well as post-disturbance deadwood legacies and recovery can enhance protective effects over time. However, most of the included studies report at least partially negative impacts of global change on avalanche protection by forests, especially under exacerbating climate change scenarios.

The evidence on how global change impacts avalanche protective forests is still limited, with most research conducted in the European Alps and analyses mainly relying on simulation models rather than on empirical data. This lack of direct evidence is partly related to the difficulty in measuring forest effects on avalanche release and runout, the limited number of continuous and systematic observations as well as the complexity of forest ecosystems' responses to changing climate conditions linked to management interventions. However, only two studies have investigated how climate-driven treeline shifts affect the protective effects of forests, even though such shifts are well-documented (e.g., Cudlín et al., 2017).

Our review underscores the importance of an active and adaptive forest management in response to global change impacts. Strategies like thinning and the promotion of natural tree regeneration are often recommended to improve forest resilience, but their effect on avalanche protection by forests requires careful consideration. That is, there is a need for further research on the effects of current forest management practices, as their impact on protective effects against avalanches varies depending on local context and climate scenarios. Moreover, active and adaptive management may also leverage large-scale natural disturbances to drive needed transformations in tree species compositions of protective forests, optimizing their fitness (Scherrer et al., 2023), or actively introduce tree species that are more suitable to future climates (Konic et al., 2024).

The common practice of salvage logging after windthrow or bark beetle outbreaks has been found to reduce the protective effect of forests against avalanches immediately and should be reevaluated as climate change increases the frequency of such disturbances. Retaining lying and standing deadwood can inhibit avalanche formation by increasing surface roughness (Baggio et al., 2022), while still influencing snow interception as well as wind and radiation regimes (Teich et al., 2019). In addition, lying deadwood can enhance protective forests' recovery by providing favorable regeneration microsites and partly protecting seedlings from ungulate browsing (Marangon et al., 2022). Moreover, natural enemy species can play a major role in regulating bark beetle populations, so removing infested trees and logs may hinder their development, thereby reducing their effectiveness (Wegensteiner et al., 2015).

Only six studies quantified the effects of changes in the protective forests on associated risks (e.g., Stritih et al., 2021; Zgheib et al., 2022a, b; Figure 3). However, quantifying the consequences for society of global change impacts on protective forests facilitates decisions on the prioritization of management interventions and the allocation of resources (Teich and Bebi, 2009).

Not only protective forests, but also avalanche activity is impacted by global changes showing general decreasing trends of avalanche numbers, size, seasonality and activity at low elevations, and an increase in the proportion of wet avalanches (Eckert et al., 2024), as well as decreasing weather situations associated with avalanche releases in forests (Teich et al., 2012a). All described impacts of global change challenge current and future protective forests avalanche risk management, which need to consider climatically and human-induced shifts in the vulnerability, importance and capability of forests providing avalanche protection (Teich et al., 2012b).

Future research should focus on gathering more empirical data, improving modeling and evaluation approaches, and investigating the effects of compound events, such as droughts followed by forest fires, on protective effects of forests against snow avalanches. We recommend: 1) enhancing large-scale monitoring of global change impacts on protective forests, 2) conducting detailed local assessments of the interactions between different effects, 3) improving and combining forest simulations with snowpack and avalanche dynamics models that account for forest effects, and 4) implementing risk-based evaluations of changes in forests' protective effects. Addressing these steps will be crucial for developing proactive and sustainable management strategies for these important Nature-based Solutions in the face of ongoing global change.

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REFERENCES

References included in the systematic review are marked with*.

Albrich, K., Rammer, W., and Seidl, R.: Climate change causes critical transitions and irreversible alterations of mountain forests, Glob Chang Biol, 26, 4013–4027, https://doi.org/10.1111/gcb.15118, 2020.

*Baggio, T., Brožová, N., Bast, A., Bebi, P., and D'Agostino, V.: Novel indices for snow avalanche protection assessment and monitoring of wind-disturbed forests, Ecol Eng, 181, 106677, https://doi.org/10.1016/j.ecoleng.2022.106677, 2022.

*Bebi, P., Kulakowski, D., and Rixen, C.: Snow avalanche disturbances in forest ecosystems—State of research and implications for management, For Ecol Manage, 257, 1883–1892, https://doi.org/10.1016/j.foreco.2009.01.050, 2009.

Brang, P., Schönenberger, W., Ott, E., and Gardner, B.: Forests as Protection from Natural Hazards, in: The Forests Handbook: Applying Forest Science for Sustainable Management 2, edited by: Evans, J., Black-well Science, Oxford, 53–81, 2001.

*Caduff, M. E., Brožová, N., Kupferschmid, A. D., Krumm, F., and Bebi, P.: How large-scale bark beetle infestations influence the protective effects of forest stands against avalanches: A case study in the Swiss Alps, For Ecol Manage, 514, 120201, https://doi.org/10.1016/j.foreco.2022.120201, 2022.

Cordonnier, T., Berger, F., Elkin, C., Lämås, T., and Martinez, M.: ARANGE Deliverable D2.2 Models and linker functions (indicators) for ecosystem services (Updated version 28.03.2014), 2014.

Cudlín, P., Cudlín, P., Cudlín, P., Tognetti, R., Malis, F., Alados, C., Bebi, P., Grunewald, K., Zhiyanski, M., Andonowski, V., La Porta, N., Bratanova-Doncheva, S., Kachaunova, E., Edwards-Jonášová, M., Ninot, J., Rigling, A., Hofgaard, A., Hlásny, T., Skalák, P., and Wielgolaski, F.: Drivers of treeline shift in different European mountains, Clim Res, 73, 135–150, https://doi.org/10.3354/cr01465, 2017.

Eckert, N., Corona, C., Giacona, F., Gaume, J., Mayer, S., van Herwijnen, A., Hagenmuller, P., and Stoffel, M.: Climate change im-pacts on snow avalanche activity and related risks, Nat Rev Earth Environ, https://doi.org/10.1038/s43017-024-00540-2, 2024.

*Elkin, C., Gutiérrez, A. G., Leuzinger, S., Manusch, C., Temperli, C., Rasche, L., and Bugmann, H.: A 2 °C warmer world is not safe for ecosystem services in the European Alps, Glob Chang Biol, 19, 1827–1840, https://doi.org/10.1111/gcb.12156, 2013.

*Frey, W. and Thee, P.: Avalanche protection of windthrow areas: A ten year comparison of cleared and uncleared starting zones, Forest Snow and Landscape Research, 77, 89–107, 2002.

*Gądek, B., Kaczka, R. J., Rączkowska, Z., Rojan, E., Casteller, A., and Bebi, P.: Snow avalanche activity in Żleb Żandarmerii in a time of climate change (Tatra Mts., Poland), Catena, 158, 201–212, https://doi.org/10.1016/j.catena.2017.07.005, 2017.

*García-Hernández, C., Ruiz-Fernández, J., Sánchez-Posada, C., Pereira, S., Oliva, M., and Vieira, G.: Reforestation and land use change as drivers for a decrease of avalanche damage in mid-latitude mountains (NW Spain), Glob Planet Change, https://doi.org/10.1016/j.gloplacha.2017.05.001, 2017.

*Germain, D., Filion, L., and Hétu, B.: Snow avalanche activity after fire and logging disturbances, northern Gaspé Peninsula, Quebec, Canada, Can J Earth Sci, 42, 2103–2116, https://doi.org/10.1139/e05-087, 2005.

Getzner, M., Gutheil-Knopp-Kirchwald, G., Kreimer, E., Kirchmeir, H., and Huber, M.: Gravitational natural hazards: Valuing the protective function of Alpine forests, For Policy Econ, 80, 150–159, https://doi.org/10.1016/j.forpol.2017.03.015, 2017.

*Grätz, T., Vospernik, S., and Scheidl, C.: Evaluation of afforestations for avalanche protection with orthoimages using the random forest algorithm, Eur J For Res, https://doi.org/10.1007/s10342-023-01640-2, 2024.

*Hillebrand, L., Marzini, S., Crespi, A., Hiltner, U., and Mina, M.: Contrasting impacts of climate change on protection forests of the Italian Alps, Frontiers in Forests and Global Change, 6, https://doi.org/10.3389/ffgc.2023.1240235, 2023.

*Irauschek, F., Rammer, W., and Lexer, M. J.: Can current management maintain forest landscape multifunctionality in the Eastern Alps in Austria under climate change?, Reg Environ Change, 17, 33–48, https://doi.org/10.1007/s10113-015-0908-9, 2017a.

*Irauschek, F., Rammer, W., and Lexer, M. J.: Evaluating multifunctionality and adaptive capacity of mountain forest management alternatives under climate change in the Eastern Alps, Eur J For Res, 136, 1051–1069, https://doi.org/10.1007/s10342-017-1051-6, 2017b.

*Konic, J., Heiling, C., Haeler, E., Chakraborty, D., Lapin, K., and Schueler, S.: The potential of non-native tree species to provide major ecosystem services in Austrian forests, Front Plant Sci, 15, https://doi.org/10.3389/fpls.2024.1402601, 2024.

*Kupferschmid Albisetti, A. D., Brang, P., Schönenberger, W., and Bugmann, H.: Decay of Picea abies snag stands on steep mountain slopes, The Forestry Chronicle, 79, 247–252, https://doi.org/10.5558/tfc79247-2, 2003.

*Leverkus, A. B., Buma, B., Wagenbrenner, J., Burton, P. J., Lingua, E., Marzano, R., and Thorn, S.: Tamm review: Does salvage logging mitigate subsequent forest disturbances?, For Ecol Manage, 481, 118721, https://doi.org/10.1016/j.foreco.2020.118721, 2021.

*Mainieri, R., Favillier, A., Lopez-Saez, J., Eckert, N., Zgheib, T., Morel, P., Saulnier, M., Peiry, J. L., Stoffel, M., and Corona, C.: Impacts of land-cover changes on snow avalanche activity in the French Alps, Anthropocene, 30, 100244, https://doi.org/10.1016/j.ancene.2020.100244, 2020.

Marangon, D., Marchi, N., and Lingua, E.: Windthrown elements: a key point improving microsite amelioration and browsing protection to transplanted seedlings, For Ecol Manage, 508, 120050, https://doi.org/10.1016/j.foreco.2022.120050, 2022.

*Maroschek, M., Rammer, W., and Lexer, M. J.: Using a novel assessment framework to evaluate protective functions and timber production in Austrian mountain forests under climate change, Reg Environ Change, 15, 1543–1555, https://doi.org/10.1007/s10113-014-0691-z, 2015.

*Mathys, A. S., Bottero, A., Stadelmann, G., Thürig, E., Ferretti, M., and Temperli, C.: Presenting a climate-smart forestry evaluation framework based on national forest inventories, Ecol Indic, 133, 108459, https://doi.org/10.1016/j.ecolind.2021.108459, 2021.

*Mayer, A. C. and Stöckli, V.: Long-term impact of cattle grazing on subalpine forest development and efficiency of snow avalanche protection, Arct Antarct Alp Res, 37, 521–526, 2005.

*McClung, D. M.: Characteristics of terrain, snow supply and forest cover for avalanche initiation caused by logging, Ann Glaciol, 32, 223–229, https://doi.org/10.3189/172756401781819391, 2001.

*Mina, M., Bugmann, H., Cordonnier, T., Irauschek, F., Klopcic, M., Pardos, M., and Cailleret, M.: Future ecosystem services from European mountain forests under climate change, Journal of Applied Ecology, 54, 389–401, https://doi.org/10.1111/1365-2664.12772, 2017.

Moos, C., Bebi, P., Schwarz, M., Stoffel, M., Sudmeier-Rieux, K., and Dorren, L.: Ecosystem-based disaster risk reduction in mountains, Earth Sci Rev, 177, 497–513, https://doi.org/10.1016/j.earscirev.2017.12.011, 2018.

Moos, C., Stritih, A., Teich, M., and Bottero, A.: Mountain protective forests under threat? an in-depth review of global change impacts on their protective effect against natural hazards, Frontiers in Forests and Global Change, 6, https://doi.org/10.3389/ffgc.2023.1223934, 2023.

Olschewski, R., Bebi, P., Teich, M., Wissen Hayek, U., and Grêt-Regamey, A.: Avalanche protection by forests—A choice experiment in the Swiss Alps, For Policy Econ, 15, 108–113, https://doi.org/10.1016/j.forpol.2011.10.002, 2012.

*Oven, D., Žabota, B., and Kobal, M.: The influence of abiotic and biotic disturbances on the protective effect of alpine forests against avalanches and rockfalls, Acta Silvae et Ligni, 121, 1–18, https://doi.org/10.20315/ASetL.121.1, 2020.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., and Moher, D.: The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ, 372, https://doi.org/10.1136/bmj.n71, 2021.

*Rammig, A., Fahse, L., Bugmann, H., and Bebi, P.: Forest regeneration after disturbance: A modelling study for the Swiss Alps, For Ecol Manage, 222, 123–136, https://doi.org/10.1016/j.foreco.2005.10.042, 2006.

*Rammig, A., Fahse, L., Bebi, P., and Bugmann, H.: Wind disturbance in mountain forests: Simulating the impact of management strategies, seed supply, and ungulate browsing on forest succession, For Ecol Manage, 242, 142–154, https://doi.org/10.1016/j.foreco.2007.01.036, 2007.

Scherrer, D., Allgaier Leuch, B., Fischer, C., Frehner, M., and Wohlgemuth, T.: Maintaining the protective function of mountain forests under climate change by the concept of naturalness in tree species composition, Frontiers in Forests and Global Change, 6, https://doi.org/10.3389/ffgc.2023.1191639, 2023.

*Schönenberger, W., Noack, A., and Thee, P.: Effect of timber removal from wind-throw slopes on the risk of snow avalanches and rockfall, For Ecol Manage, 213, 197–208, https://doi.org/10.1016/j.foreco.2005.03.062, 2005.

*Stritih, A., Bebi, P., Rossi, C., and Grêt-Regamey, A.: Addressing disturbance risk to mountain forest ecosystem services, J Environ Manage, 296, 113188, https://doi.org/10.1016/j.jenvman.2021.113188, 2021.

*Stritih, A., Senf, C., Marsoner, T., and Seidl, R.: Mapping the natural disturbance risk to protective forests across the European Alps, J Environ Manage, 366, 121659, https://doi.org/10.1016/j.jenvman.2024.121659, 2024.

*Teich, M. and Bebi, P.: Evaluating the benefit of avalanche protection forest with GIS-based risk analyses—A case study in Switzerland, For Ecol Manage, 257, 1910–1919, https://doi.org/10.1016/j.foreco.2009.01.046, 2009.

Teich, M., Marty, C., Gollut, C., Grêt-Regamey, A., and Bebi, P.: Snow and weather conditions associated with avalanche releases in forests: Rare situations with decreasing trends during the last 41years, Cold Reg Sci Technol, 83–84, 77–88, https://doi.org/10.1016/j.coldregions.2012.06.007, 2012a.

Teich, M., Zurbriggen, N., Bartelt, P., Grêt-Regamey, A., Marty, C., Ulrich, M., and Bebi, P.: Potential impacts of climate change on snow avalanches starting in forested terrain, in: 2012 International Snow Science Workshop, Anchorage, Alaska, 244–251, 2012b.

*Teich, M., Giunta, A. D., Hagenmuller, P., Bebi, P., Schneebeli, M., and Jenkins, M. J.: Effects of bark beetle attacks on forest snowpack and avalanche formation – Implications for protection forest management, For Ecol Manage, 438, 186–203, https://doi.org/10.1016/j.foreco.2019.01.052, 2019.

*Thrippleton, T., Lüscher, F., and Bugmann, H.: Climate change impacts across a large forest enterprise in the Northern Pre-Alps: dynamic forest modelling as a tool for decision support, Eur J For Res, 139, 483–498, https://doi.org/10.1007/s10342-020-01263-x, 2020.

*Thrippleton, T., Temperli, C., Krumm, F., Mey, R., Zell, J., Stroheker, S., Gossner, M. M., Bebi, P., Thürig, E., and Schweier, J.: Balancing disturbance risk and ecosystem service provisioning in Swiss mountain forests: an increasing challenge under climate change, Reg Environ Change, 23, https://doi.org/10.1007/s10113-022-02015-w, 2023.

*Vacchiano, G., Berretti, R., Mondino, E. B., Meloni, F., and Motta, R.: Assessing the Effect of Disturbances on the Functionality of Direct Protection Forests, Mt Res Dev, 36, 41–55, 2016.

Wegensteiner, R., Wermelinger, B., and Herrmann, M.: Natural Enemies of Bark Beetles, in: Bark Beetles, Elsevier, 247–304, https://doi.org/10.1016/B978-0-12-417156-5.00007-1, 2015.

*Wohlgemuth, T., Schwitter, R., Bebi, P., Sutter, F., and Brang, P.: Post-windthrow management in protection forests of the Swiss Alps, Eur J For Res, 136, 1029–1040, https://doi.org/10.1007/s10342-017-1031-x, 2017.

*Zgheib, T., Giacona, F., Granet-Abisset, A.-M., Morin, S., and Eckert, N.: One and a half century of avalanche risk to settlements in the upper Maurienne valley inferred from land cover and socio-environmental changes., Global Environmental Change, 65, 102149, https://doi.org/10.1016/j.gloenvcha.2020.102149, 2020.

*Zgheib, T., Giacona, F., Morin, S., Granet-Abisset, A.-M., Favier, P., and Eckert, N.: Diachronic quantitative snow avalanche risk assessment as a function of forest cover changes, Journal of Glaciology, 1–19, https://doi.org/10.1017/jog.2022.103, 2022a.

*Zgheib, T., Giacona, F., Granet-Abisset, A.-M., Morin, S., Lavigne, A., and Eckert, N.: Spatio-temporal variability of avalanche risk in the French Alps, Reg Environ Change, 22, 8, https://doi.org/10.1007/s10113-021-01838-3, 2022b.