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Mountain protective forests under threat? an in-depth review of global change impacts on their protective effect against natural hazards

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Forests in mountain areas provide an indispensable ecosystem service by protecting people and infrastructure against natural hazards. As forests are increasingly affected by global change, including climate change, more frequent and severe natural disturbances, and shifts in land use, open questions remain regarding the long-term and sustainable provision of this crucial protective service. To improve our understanding of the various effects of global change on protective forests, we summarized the current knowledge based on a systematic review. Focusing on changes in mountain forests' protective effect against snow avalanches, landslides, rockfall, torrential floods and debris flow, we assessed 72 peer-reviewed, English publications. Overall, climate-induced changes are expected to increase forests' protective effect at higher elevations but reduce it at lower elevations mainly due to increased drought. Natural disturbances usually decrease the protective effect of forests, and their impact is often further exacerbated by salvage logging. Different forest management strategies are often studied using forest simulation models, and their impacts on protective forests strongly depend on the local context and interactions with climate change. While clearcuts consistently reduce the protective effect, other forest management interventions such as thinning can have either positive or negative effects. Most of the reviewed studies were case studies based on forest simulation or process-based hazard models (but rarely combining the two), while empirical evidence was scarce. Forests' protective effect is often assessed using (diverse) indicators of forest structure, but evaluations of resulting risks are less common. More consistent modeling approaches linking forest structure to hazard and risk, as well as consistent indicators across different case studies, are needed for a better understanding of changes in protective forests and the service they provide under global change.

KEYWORDS

protective forest, nature-based solution, disturbance, avalanche, rockfall, landslide, torrential flood, climate change

1. Introduction

Forest ecosystems provide multiple goods and services to society, such as natural habitat for endangered plant and animal species, timber and non-wood forest products, freshwater, as well as key recreational and cultural values (Jenkins and Schaap, 2018; Winkel et al., 2022). In mountain areas, a key role of forests is the protection of people and infrastructure against the impacts of natural hazards, such as snow avalanches, landslides, rockfall or torrential floods and debris flows (Brang et al., 2001; Sudmeier-Rieux et al., 2021; Teich et al., 2022a). Numerous studies have shown the high effectiveness of forests in mitigating damages from these natural hazards (e.g., Olschewski et al., 2012; Moos et al., 2017; Bhattacharjee and Behera, 2018; Gehring et al., 2019; Grima et al., 2020). These so-called protective forests are a nature-based solution that can serve similar functions as technical (gray) infrastructure, such as avalanche barriers or rockfall nets, but usually at lower costs, while also providing a wide array of co-benefits (Getzner et al., 2017; Ruangpan et al., 2020). However, adverse impacts of global change on mountain forests are becoming increasingly evident (e.g., Mina et al., 2017; Albrich et al., 2020), raising questions about their long-term and sustainable capacity to provide protection from natural hazards (Makino and Rudolf-Miklau, 2021).

Protective forests are forests that have the primary function of reducing the risk of natural hazards for settlements and infrastructure by affecting one or several risk components, namely the hazard, exposure, and vulnerability (Brang et al., 2001; IPCC, 2012). The hazard refers to the occurrence probability of an event that can potentially cause damage (UNISDR, 2009). Forests can reduce the hazard by either preventing the release of a mass (e.g., snow avalanches, landslides) or hindering its downslope propagation (e.g., rockfall, snow avalanches), thus reducing its onset and/or propagation probability (Moos et al., 2018). Exposure is a measure of the possible loss that may result from the impacts of a damaging event on people and their properties (UNISDR, 2009). By dissipating energy and retaining material, forests can reduce the intensity of a natural hazard process and, consequently, the extent of damage (Poratelli et al., 2020). Vulnerability describes the degree of physical, economic, societal, or environmental loss caused by a natural hazard event (Fritzsche et al., 2014). It can be reduced by forests as they provide communities with resources to withstand and recover from damaging events (Sudmeier-Rieux et al., 2021). The degree to which a forest can mitigate risks emanating from natural hazards corresponds to its “protective effect” (Brang et al., 2001; Teich et al., 2022a), which largely depends on the forest extent, structure, and composition, but also on the magnitude of the natural hazard event (Schwarz et al., 2010; Moos et al., 2016; Costa et al., 2021; Perzl et al., 2021).

Generally, protective forests represent a sustainable and reliable protection system (Moos et al., 2019a). However, since forest ecosystems are dynamic, their protective effect is also subject to fluctuations. Direct anthropogenic impacts, such as land-use change or forest management interventions, can alter the extent and structure of protective forests (e.g., Bigot et al., 2009; Vergani et al., 2016). Natural forest dynamics and disturbances can result in temporary or irreversible loss of the protective effect, and these dynamics are being accelerated by climate change (e.g., Wohlgemuth et al., 2017; Teich et al., 2019; Oven et al., 2020; Caduff et al., 2022). At the same time, rising air temperatures and

more frequent and severe drought periods will lead to shifts in tree species distribution and forest composition, which may impact their protective effect differently depending on the type of natural hazard. The uncertainties related to these changes pose great challenges for the sustainable management of protective forests and the key ecosystem services they provide in mountain areas (Thrippleton et al., 2023).

This review seeks to synthesize the various types of global change impacts on protective forests, as independent or interacting factors. We therefore conducted a state-of-the-art systematic analysis of the English-language and peer-reviewed literature, examining the influence of global change on protective forests. We focused on climate - or anthropogenic-driven changes, as well as (changing) natural disturbance regimes and their implications for the protective effect of forests. We constrained the assessment to protective forests situated in mountain areas that are characterized by changes in elevation over short distances. These forests directly protect against the gravity-driven natural hazards snow avalanches, rockfall, landslides, torrential floods, and debris flows. Our review provides an overview of the existing literature, including the geographical distribution of the studies, the considered hazard processes, and types of global change impacts, as well as the methods applied to detect the changes in forests’ protective effect. Based on our analysis, we discuss the interactions of different global change impacts and identify knowledge gaps and future research avenues, which may help shape future research programs and inform forest management.

2. Methods

2.1. Literature search

We conducted a systematic literature research following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) method to ensure transparency (Page et al., 2021). In a first step, we identified potentially relevant publications based on searches with predefined search terms in the two databases *Web of Science* and *CAB Abstracts* (Figure 1). We therefore combined “protective forest” terms with terms concerning “global change” and the “protective service” (Table 1). We searched for the respective terms in the title, keywords and/or the abstract. This resulted in 797 papers from *Web of Science* and 247 from *CAB Abstracts*. They were retrieved on August 4, 2022. We expanded our search with results from *Google Scholar*, by searching for the terms “protective forest” and “climate change” as well as “impact of global change on protective forests” (27 additional articles) and with publications we had known before and judged as relevant, but which were not included in the results of the initial search (6 additional publications). We then screened the publication’s titles and abstracts to assess whether they were thematically relevant or not. Only papers that specifically addressed changes in forests’ protective effect against natural hazards in mountain areas under global change were included in the subsequent detailed review. The detailed inclusion criteria are reported in Table 2. We further excluded “gray” literature (e.g., non-peer reviewed documents and reports) as well as non-English publications. This resulted in a total of 72 relevant publications (Supplementary Table S1).

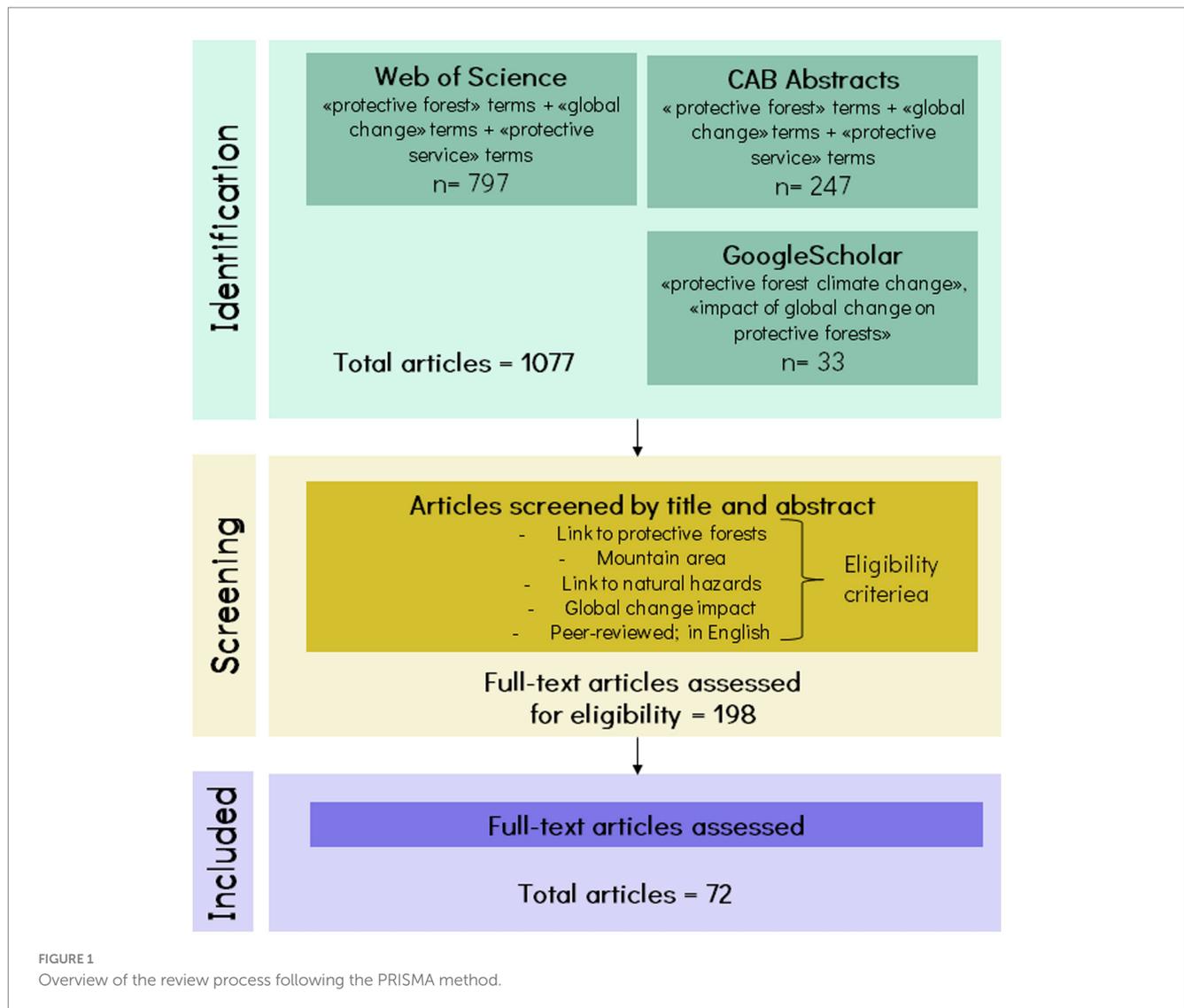


TABLE 1 Applied search terms per category.

Category	Search terms
Protective forest	forest* OR “protection forest” OR “protective forest” OR “Eco-DRR”
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	“natural hazard” OR “risk reduction” OR “protective effect” OR “protection effect” OR “protective function” OR “protection function” OR “protective capacity” OR avalanche OR landslide OR flood OR rockfall OR “peak flow” OR “debris flow”

2.2. Literature assessment and data analysis

In a next step, the author team reviewed the relevant publications following a systematic protocol (Supplementary Table S2). For each

publication, basic information, such as the investigated natural hazard process(es), the country and location, the forest type, or the considered elevation range, were recorded. We further categorized the studies based on the addressed type(s) of global change impact, distinguishing three different main types:

- Climate-induced forest change: Change in forest extent, structure or composition due to the direct effect of changing climate (e.g., altering growth conditions / mortality due to changing air temperature and precipitation; treeline shift);
- (Changing) natural disturbances: Forest change following natural disturbance (e.g., forest fires, windthrow, insects and pathogens, mass movements);
- Anthropogenic forest change: Change in forest extent, structure, or composition due to direct human influence (e.g., land-use change, management interventions, de-/afforestation, introduction of alien species).

We assessed whether forests changed in their (i) composition, (ii) structure, and/or (iii) extent (see Supplementary Table S2).

TABLE 2 Criteria applied to the search results to select papers for the detailed review.

Criteria	Specifications
Mountain area	Mountain area defined as area with elevation difference potentially resulting in gravity-driven processes; e.g., exclusion of studies on mangrove forests, floodplain forests or urban areas. We considered mountain areas all over the world, including a large variety of forest types.
Natural hazards	Papers studying the protective effect of forests on gravity-driven natural hazards, including landslides, snow avalanches, rockfall, torrential floods, debris flows. Papers without a clear link to these natural hazards / “extreme” events were excluded (e.g., papers on general hydrological effects of forests or soil protection).
Global change impacts	Papers studying the changes in protective forests related to climate change (e.g., increasing drought or altering natural disturbances) or anthropogenic changes (e.g., management interventions, land-use change). Papers examining the protective effect of forests against natural hazards were included only if they established a clear link between the protective effect and forest changes related to global change impacts. Papers focusing on the general role of forests in climate change mitigation were excluded.
Publication type	Peer-reviewed articles, books, book chapters, conference papers in English; exclusion of “gray literature” and pre-prints.

We recorded any changes in the protective effect of forests due to the global change impacts revealed by the studies, classifying them in five categories (increase, decrease, no change, scenario-dependent, inconclusive). In case different scenarios were considered in a study, we determined the forest changes and their impacts on the protective effect for each scenario. Additionally, the methodologies used by the studies to assess a change in the protective effect were characterized (field-based/empirical; statistical modeling; numerical/process-based modeling; experimental; expert estimation; participatory studies; review) and the variables used to characterize the change were assessed. It was then evaluated whether these were (i) qualitative or quantitative, and (ii) directly associated with the different effects of forests on natural hazards (i.e., effect on the frequency, magnitude/intensity, or risk of the hazard), or rather related to forest structure and thus only indirectly to the protective effect. The variables and methods used were analyzed per hazard type. When available, the quantitative changes in protective effect were extracted (see summary [Supplementary Table S1](https://doi.org/10.5281/zenodo.8232212) and full review table: <https://doi.org/10.5281/zenodo.8232212>).

In a final step, the different categories of global change impact were analyzed in more depth to detect differences, generalities, and potential interactions between the different global change impacts. In particular, we assessed how protective forests at different elevations were affected by climate change, and how different types of management and disturbances influenced their protective effect. Due to the wide range of different variables used to quantify the changes in the protective effect, as well as the different temporal and spatial scales analyzed by the studies, the quantitative results of different studies could not be summarized in a quantitative analysis, so we focused on the direction of changes reported in the reviewed studies.

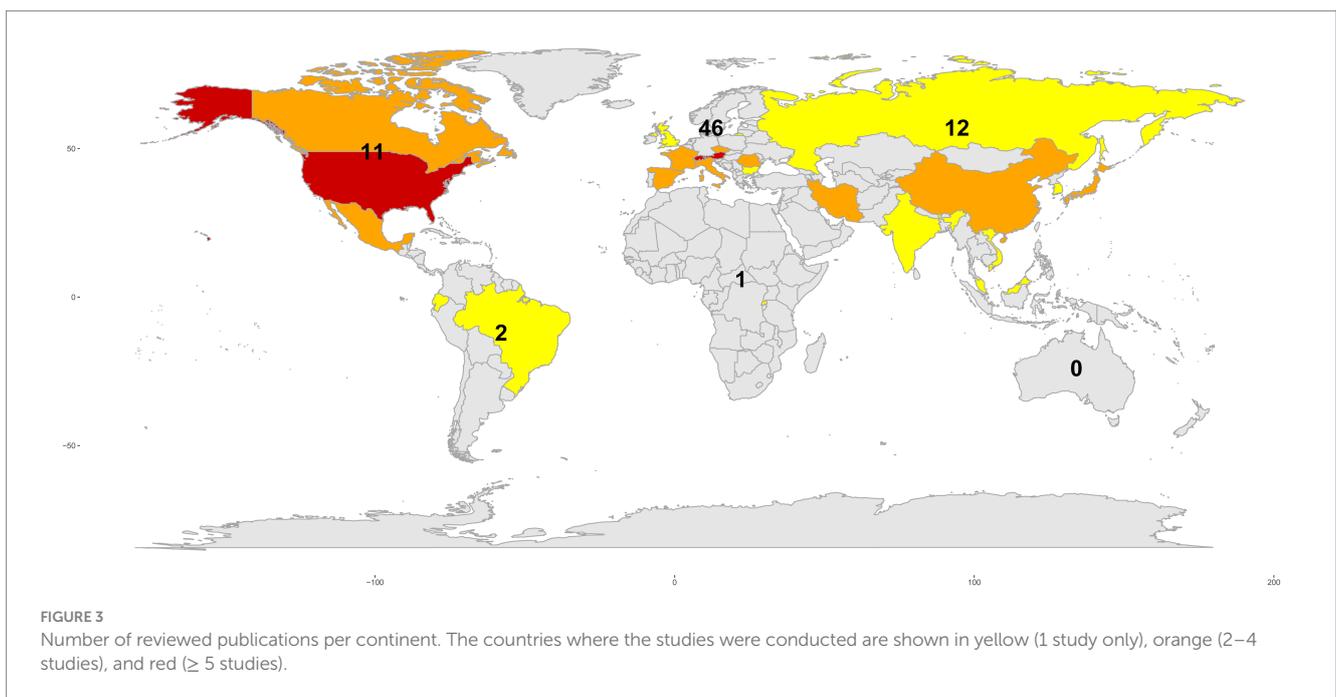
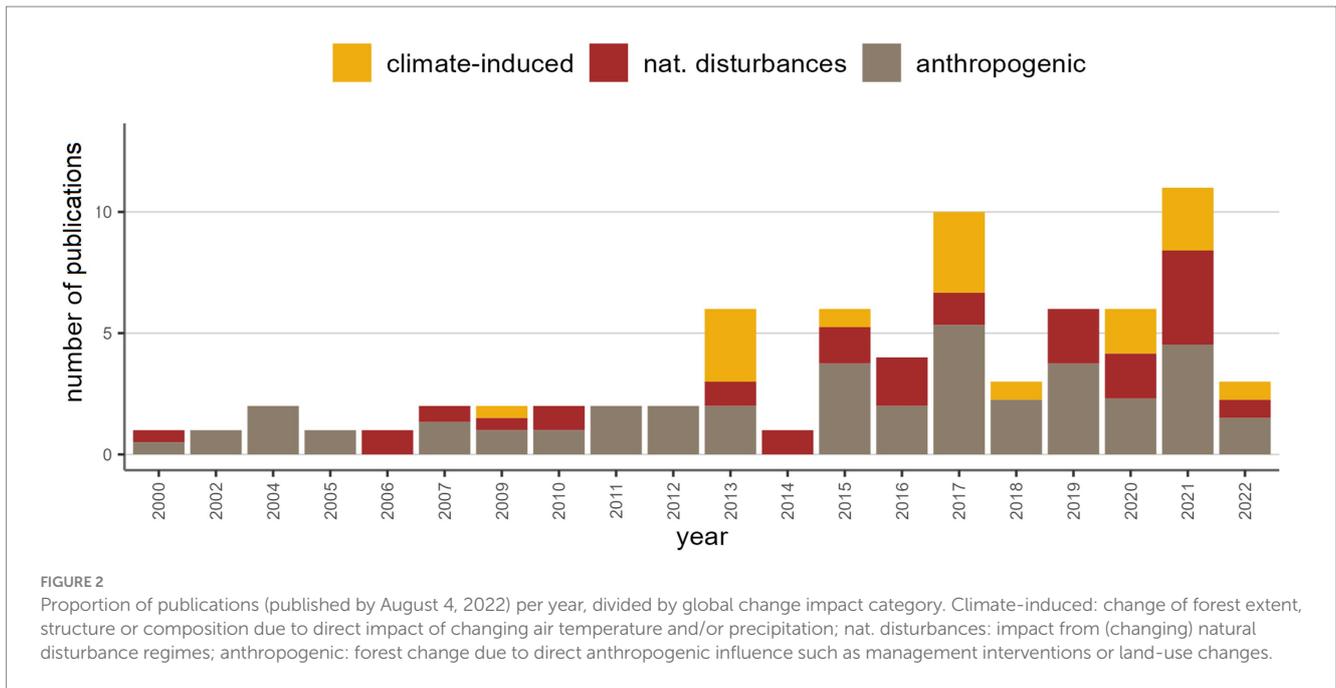
3. Results

3.1. General overview

The first publications assessed in this review were from 2000. The number continuously increased with two peaks in 2017 (10 publications) and in 2021 (11 publications). Anthropogenic - and natural disturbance-related impacts on the protective effect of forests were addressed throughout the observation period (any time until August 4, 2022), while the first publication looking at climate-induced forest change was published in 2009, followed by more publications in 2013 ([Figure 2](#)). A clear increase was observed in studies about the impacts of natural disturbances, which may be related to the emerging research following unprecedented bark beetle outbreaks in high elevation forests in the United States since the early 2000s ([Bentz et al., 2010](#); [Logan et al., 2010](#)) or the big storm events in Central Europe in the 1990s (Vivian and Lothar; [Wohlgemuth and Brang, 2015](#)). Overall, the majority of studies addressed anthropogenic impacts on protective forests (74%), followed by effects of natural disturbances (38%) and climate-induced forest change (28%), whereas about one third of the studies looked at coupled/interacting effects. The studies were predominantly carried out in Europe, followed by North America and Asia. Only two studies looked at global change impacts on forests’ protective effect in South America, and one in Africa ([Figure 3](#)).

Approximately one third of the studies investigated the protective effect against rockfall, landslides and/or snow avalanches, while 43% addressed floods and only two studies addressed debris flow. Most studies were based on quantitative methods (82%), a large proportion of which used numerical or process-based modeling to assess global change impacts (56% of total studies; [Figure 4](#)). Among these, commonly used models include forest simulation models, such as iLand ([Scheidl et al., 2020](#)), PICUS ([Maroschek et al., 2015](#); [Pardos et al., 2017](#); [Zlatanov et al., 2017](#); [Irauschek et al., 2017a,b](#)), MASSIMO ([Mathys et al., 2021](#)), TreeMig ([Moos et al., 2021](#)) and ForClim ([Elkin et al., 2013](#); [Mina et al., 2017](#); [Thrippleton et al., 2020](#)), as well as process-based hydrological models (e.g., [Seibert et al., 2010](#); [Versini et al., 2013](#); [Surfleet et al., 2014](#)). However, forest simulation models and process-based models of natural hazards are only rarely combined (but see, e.g., [Scheidl et al., 2020](#); [Moos et al., 2021](#)). Field-based or empirical data were used in 32% of the reviewed studies, while the rest applied statistical modeling (20%) or was based on expert estimation, review, participatory methods, or experiments (23%). The field-based / empirical studies and those using statistical modeling predominantly assessed the protective effect against floods, while the studies using numerical models mainly focused on rockfall, followed by avalanches, landslides, and floods in equal proportion.

A mere 15% of the studies took into account the risk posed by natural hazard processes (i.e., potential consequences). Among these, only about two thirds ($n = 7$) utilized a quantitative, or at least partly quantitative, measure of natural hazard risk ([Figure 5, d](#)). Four of these publications treated the protective effect of forests against rockfall ([Farvacque et al., 2019](#); [Moos et al., 2019a,b, 2021](#)) two against avalanches ([García-Hernández et al., 2017](#); [Stritih et al., 2021](#)) and one against floods ([Bhattacharjee and Behera, 2018](#)). Most of the publications addressing floods used a measure of process intensity/magnitude to assess the protective effect, the majority of which was “peak flow” ([Figure 5, c](#)). A large proportion of the studies

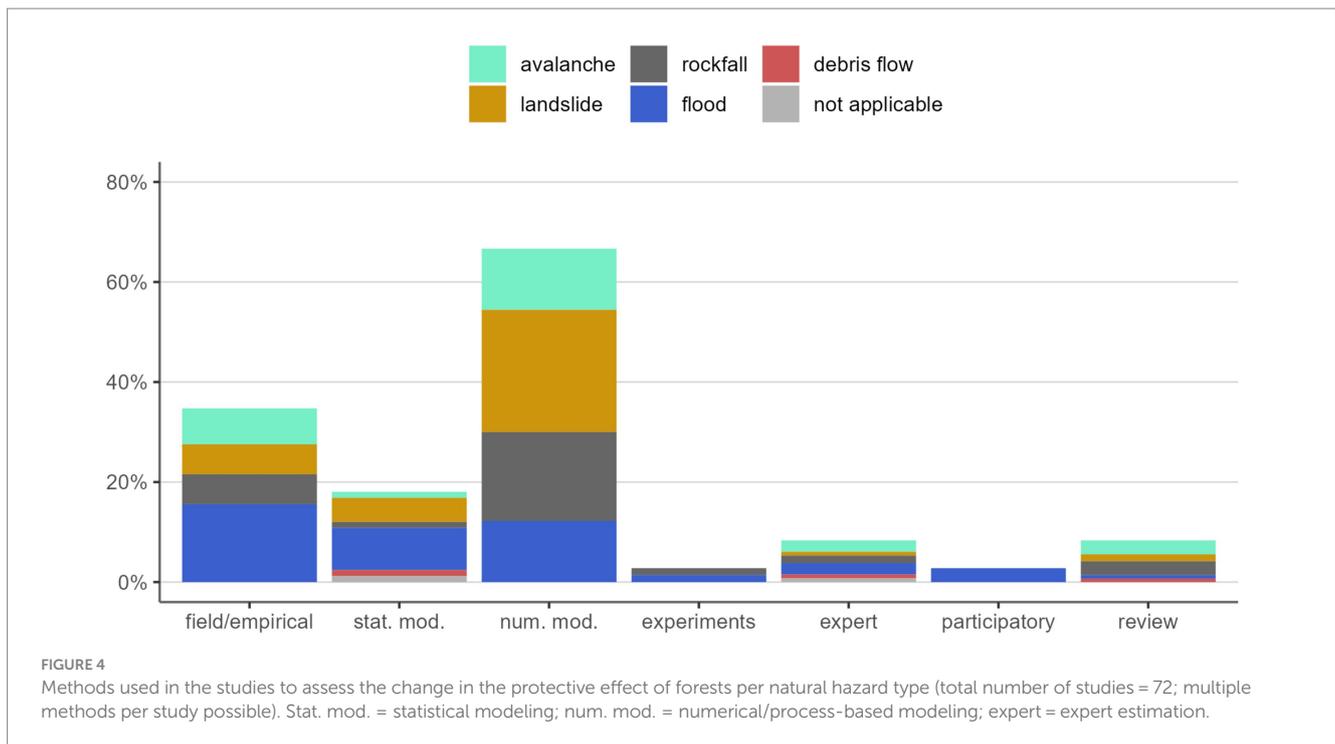


dealing with rockfall, avalanches and landslides assessed the protective effect indirectly based on forest structure characteristics. Mostly, they used a protective forest index (Figure 5, a) based on different combinations of forest parameters such as stem density and species composition. Most landslide studies used a measure of hazard frequency (e.g., landslide susceptibility or event frequency; Figure 5, b).

About half of the studies (52%) solely addressed the protective service of forests, while the others investigated multiple ecosystem services (13% wood production, 14% biodiversity, the remaining climate regulation, and water and soil services).

3.2. Climate-induced forest change

Almost one third of the publications ($n=19$) considered the impacts of climate-induced forest changes on the protective effect. They all addressed changes in forest composition or structure, and only two addressed a change in forest extent (Bebi et al., 2009; Lingua et al., 2020). Most of these studies ($n=16$; reviews excluded) were “predictive,” meaning that they assessed potential future forest changes. Observation-based studies examining the effect of past and current climate change on the protective effect were generally lacking. Borgniet et al. (2013) found a decrease in the protective effect of



forests in the Aosta Valley (Italy) between 2000 and 2009 due to a dieback of *Pinus sylvestris* based on remote sensing data, while Lange et al. (2013) used a space-for-time approach to assess how climate-driven changes in species composition might affect flood-protective forests.

More than half of the “predictive” studies ($n=12$) used dynamic forest simulation models to simulate future forest development under different climate scenarios (e.g., Mina et al., 2017; Irauschek et al., 2017b; Jandl et al., 2018; Moos et al., 2021). These modeling studies assessed the change in the protective effect mostly using protective forest indices of forest structure, rarely quantifying the forest’s effect on the hazard. However, Scheidl et al. (2020), for example, combined the dynamic forest model iLand (Seidl et al., 2012) with the hydrological model GEOtop (Rigon et al., 2006) and a slope stability model, while Moos et al. (2021) coupled the dynamic forest model TreeMig (Lischke et al., 2006) with a rockfall simulation model (RockyFor3D, Dorren, 2016) to predict changes in rockfall risk.

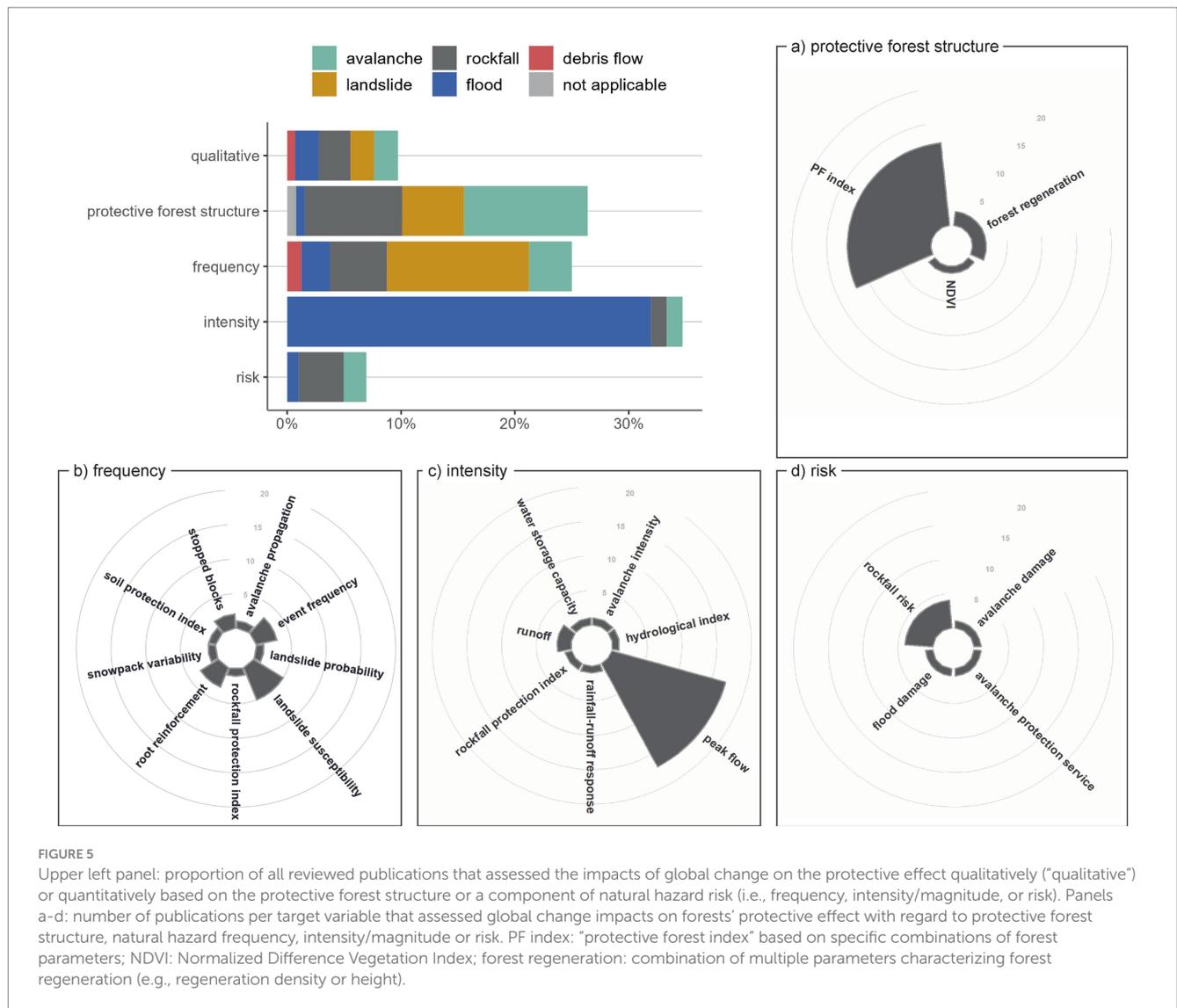
Numerous studies concur that rising air temperatures stimulate forest growth, thereby enhancing the protective role of forests at high elevations (Figure 6; e.g., Elkin et al., 2013; Mina et al., 2017; Pardos et al., 2017; Irauschek et al., 2017a,b). Furthermore, forest expansion at and above the current treeline will also likely contribute to an increased protective effect (Bebi et al., 2009). On the other hand, more frequent and severe droughts may lead to a decrease in the protective effect at lower elevations due to a decrease in growing stock caused by increased mortality and reduced growth (e.g., Elkin et al., 2013; Mina et al., 2017; Zlatanov et al., 2017; Moos et al., 2021; Figure 7). Based on the assessed studies, which predominantly originate from Europe, positive effects of increasing air temperature can generally be expected for elevations >1,500 m a.s.l., and negative effects for elevations <1,000 m a.s.l. In-between, climate change effects depend on local conditions and the climate scenario (Figure 6). Furthermore, Maroschek et al. (2015) and Irauschek et al. (2017b) reported

counterbalancing effects of climate warming on tree growth (increase in protective effect) and increasing natural disturbances (decrease in protective effect). A few studies did not find a significant change in the protective effect due to climate-induced forest cover change (e.g., Irauschek et al., 2017a in the Alps and Mina et al., 2017 in the Iberian Mountains).

3.3. (Changing) natural disturbances

Among the reviewed publications, 26 addressed how forests’ protective effect against natural hazards is affected by natural forest disturbances (such as forest fires, windthrows, and bark beetle outbreaks, see Figure 8). Natural disturbances often cause a decrease in the protective effect for years to decades after the disturbance. The impact depends on the severity of the disturbance (e.g., the level of tree mortality or the degree of change in forest structure), which was, however, often not explicitly quantified in the reviewed studies. Among different disturbance agents, forest fires were addressed most often (11 studies). Forest fires have been found to reduce forests’ flood protective effect, which can lead to increased peak flows. These effects were often studied using a combination of process-based hydrological models and observational data, with observed post-fire peak flows up to 120% higher compared to modeled pre-fire conditions (Seibert et al., 2010). However, the effects of fires on peak flows were highly variable, sometimes with no clear effects in large watersheds (Buttle and Metcalfe, 2000) or in case of low-to-moderate fire severity (Surfleet et al., 2014). Nonetheless, climate change and increased forest fire risk are expected to lead to increased flood risk, e.g., in Mediterranean watersheds (Versini et al., 2013).

After windthrow and bark beetle disturbances, management decisions had an important impact on the post-disturbance protective effect. If left in the stand, deadwood could maintain forests’ protective



effect after a disturbance (Rammig et al., 2007; Wohlgemuth et al., 2017; Teich et al., 2019; Costa et al., 2021; Caduff et al., 2022), especially during the first 15 years (Caduff et al., 2022). Rockfall simulations have shown that lying deadwood even increased forests’ protective effect (Costa et al., 2021). In contrast, salvage logging after a disturbance could further impair forests’ protective effect (Leverkus et al., 2021).

Several studies addressed the development of forests’ protective effect over time after disturbances, especially in case of insect, wind, and fire disturbances in the European Alps. For example, Caduff et al. (2022) surveyed sites affected by windthrow and bark beetles using remote sensing data and used avalanche simulations to assess the disturbed forests’ protective effect, which was lowest after deadwood was removed or decayed, approximately 10–15 years after disturbance (Caduff et al., 2022). Approximately 25 years after windthrow events, the protective effect was still judged to be insufficient based on field surveys and expert assessment (Wohlgemuth et al., 2017), while both field observations combined with rockfall simulations (Maringer et al., 2016) and forest simulation models indicate that the protective effect will recover within 40–50 years after disturbance (Rammig et al., 2007;

Moos et al., 2019a). On longer timescales, natural disturbances can have a positive influence on forests’ protective effect. For example, Scheidl et al. (2020) found that wind and bark beetle disturbances can contribute to slope stability over 50–200 years by facilitating a compositional shift from *Picea abies* toward species with deeper rooting systems (Figure 7).

Most studies on natural disturbances focused on effects at rather local scales, from single disturbed sites (especially in the case of windthrow and bark beetle) to watersheds (particularly for flood-related studies). At larger (national) scales, regularly occurring disturbances (i.e., press disturbances, including anthropogenic disturbances such as clearcutting) have been shown to have a stronger effect on the occurrence of natural hazards (flood, debris flow) than more sporadic pulses of natural disturbances (Sebald et al., 2019).

3.4. Anthropogenic forest change

Impacts of anthropogenic forest changes on the protective effect of forests were related to land-use changes (deforestation including

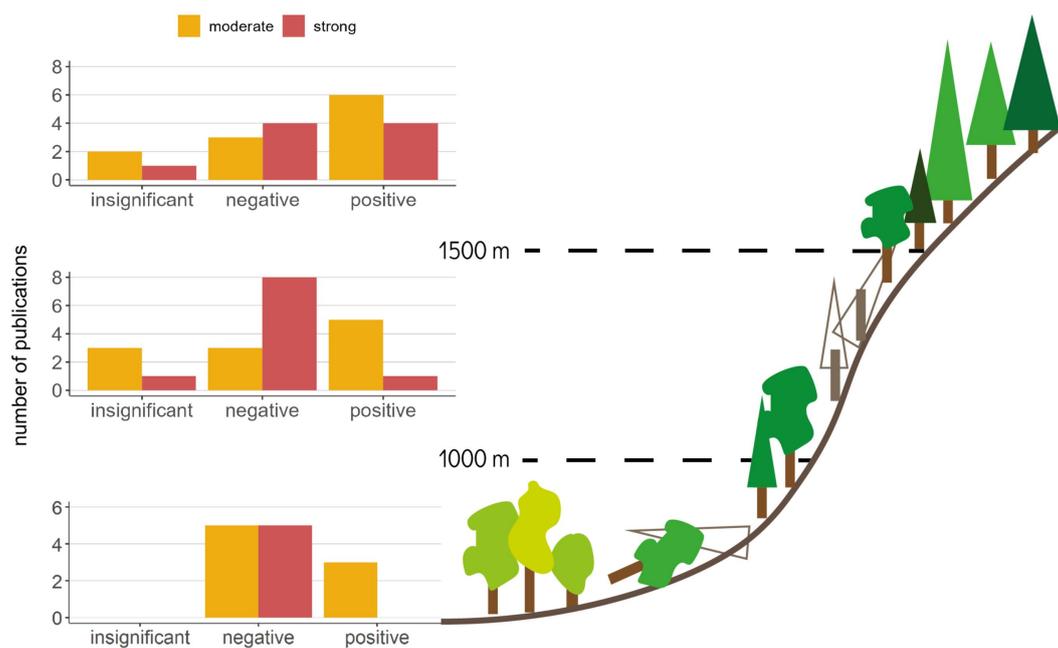


FIGURE 6

Number of publications reporting an overall positive, negative, or insignificant effect of climate-induced forest changes on the protective effect below 1,000 m a.s.l., between 1,000 and 1,500 m a.s.l. and above 1,500 m a.s.l. and for moderate (orange) and strong (red) climate change. Moderate climate change includes climate scenarios with a mean air temperature increase of ~ 1.5 – 3.5°C and no or a slight precipitation decrease of ~ 10 – 20% . Strong climate change scenarios foresee a mean air temperature increase of ~ 3.5 – 6°C and a significant precipitation decrease of ~ 20 – 40% . Overall, 14 studies reporting quantitative results were considered (reviews excluded). They originate mainly from Europe [Austria ($n = 5$), Bulgaria ($n = 1$), Italy ($n = 1$), Romania ($n = 1$), Spain ($n = 2$), Switzerland ($n = 5$)].

clear-cuts, afforestation of previously non-forested areas, and reforestation often related to the abandonment of pastures), management interventions (thinning, regeneration cuts, coppicing, and afforestation) and other human-related activities (e.g., forest grazing, introduction of invasive species, or reduced/no management activities; see Figures 7, 9). Most of the studies on anthropogenic forest change centered around deforestation, including partial clear-cuts ($n = 21$). “No management” was the second most studied determinant of change ($n = 11$), followed by regeneration cuts ($n = 9$) and thinning ($n = 7$; including different thinning methods, such as thinning from above, from below or free thinning). Reforestation ($n = 6$), afforestation ($n = 3$), and coppicing ($n = 1$) were addressed only by a few studies. One paper examined the effect of forest grazing (Mayer and Stöckli, 2005), another one the spread of invasive species (Moos et al., 2019b), and one reported anthropogenic forest change of unknown nature (Lim and Kim, 2022). Several studies (e.g., Maroschek et al., 2015; Pardos et al., 2017; Irauschek et al., 2017b; Thrippleton et al., 2020; Mathys et al., 2021) used forest simulation modeling approaches (e.g., using models like PICUS, ForClim, iLand, MASSIMO) to investigate the effect of anthropogenic forest change on the protective effect against natural hazards, solely or in interaction with moderate or strong climate scenarios.

Deforestation was mainly analyzed with respect to floods and landslides and had generally a negative impact on the protective effect provided by forests, independently of climate change (Figure 9). One study (Irauschek et al., 2017b), however, reported a positive effect of logging (in this case, clearcuts concentrated on $5,000\text{ m}^2$ strips) on the protective effect against landslides, avalanches, and rockfall under no climate change to moderate climate change scenarios, and especially when followed by artificial regeneration.

Other anthropogenic changes were mostly related to forest management and climate interactions, and their effects were strongly dependent on the considered climate change scenarios. Without climate change, “no management” mostly increased the protection against natural hazards. However, under moderate and strong climate change scenarios, negative effects of “no management” were found for landslides, avalanches, and rockfall (Irauschek et al., 2017b; Thrippleton et al., 2020). Regeneration cuts and thinning had a contrasting influence on the protective effect of forests against natural hazards under different climate scenarios (Figure 7). Positive effects of these management interventions were most often reported under no climate change, with negative effects becoming more predominant under moderate and strong climate change scenarios. However, even under strong climate change scenarios, several studies reported a relative positive influence of clearcuts (Irauschek et al., 2017b), regeneration cuts (Irauschek et al., 2017a,b; Mathys et al., 2021), thinning (Mathys et al., 2021), and the omission of management (Irauschek et al., 2017a,b) on forests’ protective effect (Figure 9), further highlighting the complexity of the interactions between climate change and direct anthropogenic influences on protective forests (Figure 7).

4. Discussion

The publications assessed in this review reported a wide range of global change impacts that were directly linked to potential changes in the protective effect of forests against natural hazards. On the one hand, a decline in forest growing stock due to more frequent and

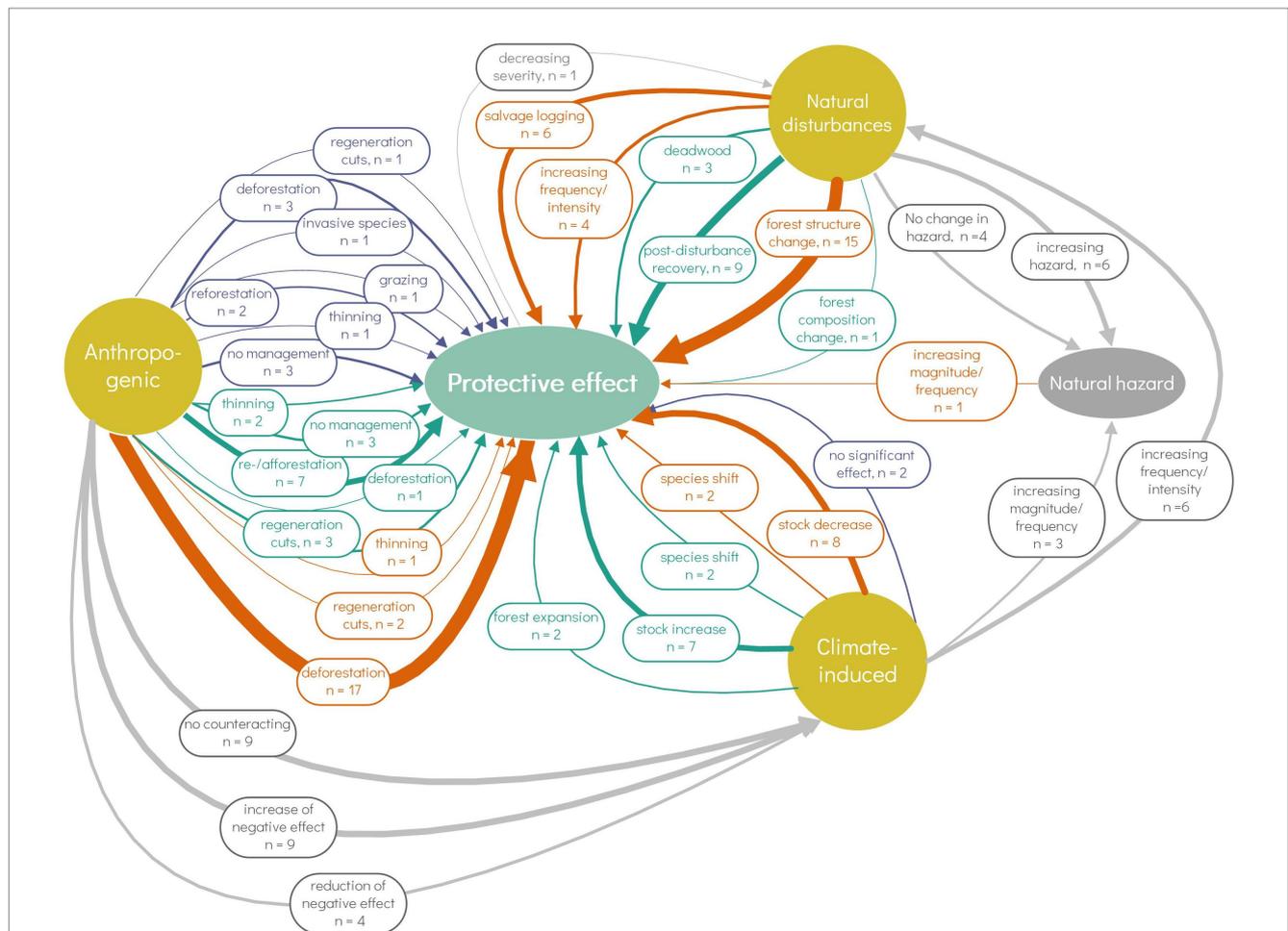


FIGURE 7 Summary of detected global change impacts on the protective effect of forests against natural hazards as well as relations/interactions between the three main impact categories “anthropogenic forest change,” “climate-induced forest change” and “natural disturbances” and/or the natural hazard. The “n” indicates the number of studies reporting a certain impact (publications are counted multiple times, if multiple scenarios were analyzed in one study). Orange arrows: “impact decreased protective effect”; green arrows: “impact increased protective effect”; purple arrows: “no or insignificant impact”; gray arrows: “relation between impact categories”.

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. On the other hand, climate change-related growth increase at high elevations, re-/afforestation as well as post-disturbance deadwood legacies and recovery can positively affect protective forests. Additionally, forest interventions aimed at promoting regeneration can in some cases increase the protective effect. Overall, most of the reviewed studies report at least partly negative effects of global change on the protective effect of forests against natural hazards, especially under exacerbating climate change scenarios.

Our review shows that evidence on global change impacts on the forests’ protective effect is relatively vague and associated with high uncertainties. In particular, impacts of changing air temperature and precipitation regimes were almost exclusively analyzed using simulation models, while empirical evidence is still largely missing. This is, however, to be expected, since the global air temperature increase is a rather recent phenomenon—at least in relation to the growth rate of trees—and forest ecosystems react to it in complex ways (e.g., Camarero et al., 2015). Likewise, studies on climate-induced

changes have only been emerging in the past 10 years. Studies on the effects of natural disturbances and anthropogenic impacts on protective forests, on the other hand, date back somewhat longer and are characterized by a greater proportion of empirical analyses. These often include the combination of data-based analyses and reconstruction of the protective forest’s change with a simulation-based assessment of its protective effect, as for example in a case study on impacts of land-use change on rockfall risk conducted by Farvacque et al. (2019). Empirical evidence on the development of the protective effect is scarce, as direct field measurements of forests’ effect on, e.g., avalanches or rockfall are difficult to obtain (Ringebach et al., 2022), and long data series on hazard events (e.g., García-Hernández et al., 2017) are rarely available (Perzl and Teich, 2022). Furthermore, the reviewed studies cover a large variety of different forest types and natural hazard dispositions, making general conclusions difficult.

Overall, the geographic distribution of the locations of the studies is very uneven, reflecting high research funds and data availability in Europe as well as the long tradition and institutional embedding of protective forest management mainly in Alpine countries. Similar geographic biases have also been shown by recent studies in the field of

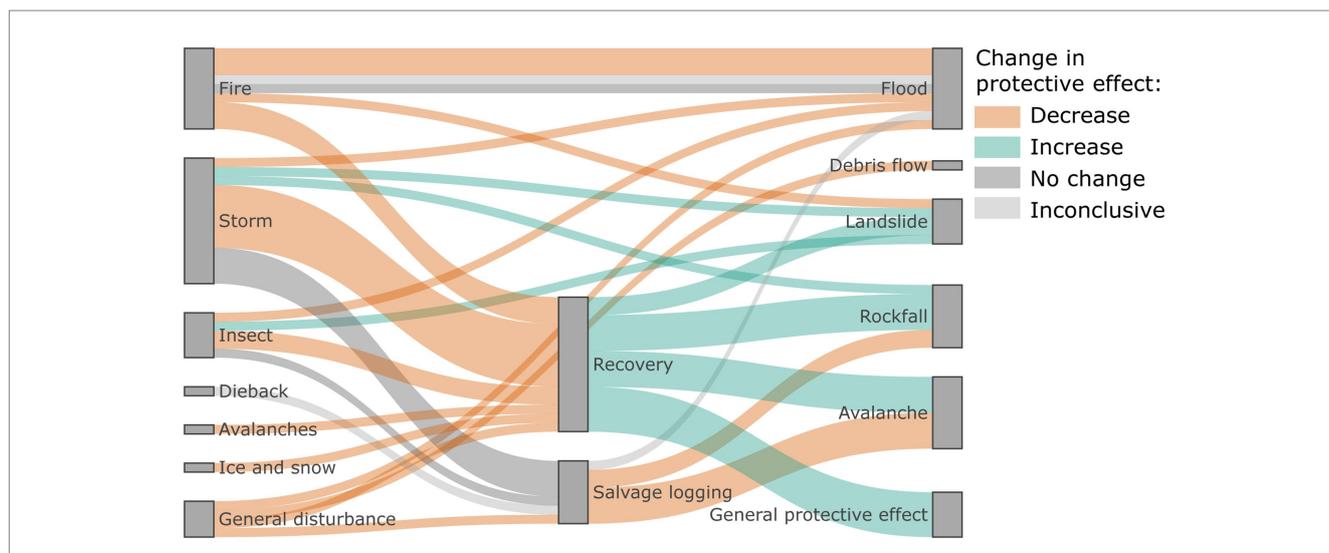


FIGURE 8 Impacts of natural disturbances (left) on the protective effect against different types of natural hazards (right), mediated by processes of salvage logging and forest recovery. The width of the connections corresponds to the number of studies that examined a specific link, where studies examining multiple effects or scenarios are represented multiple times in the figure.

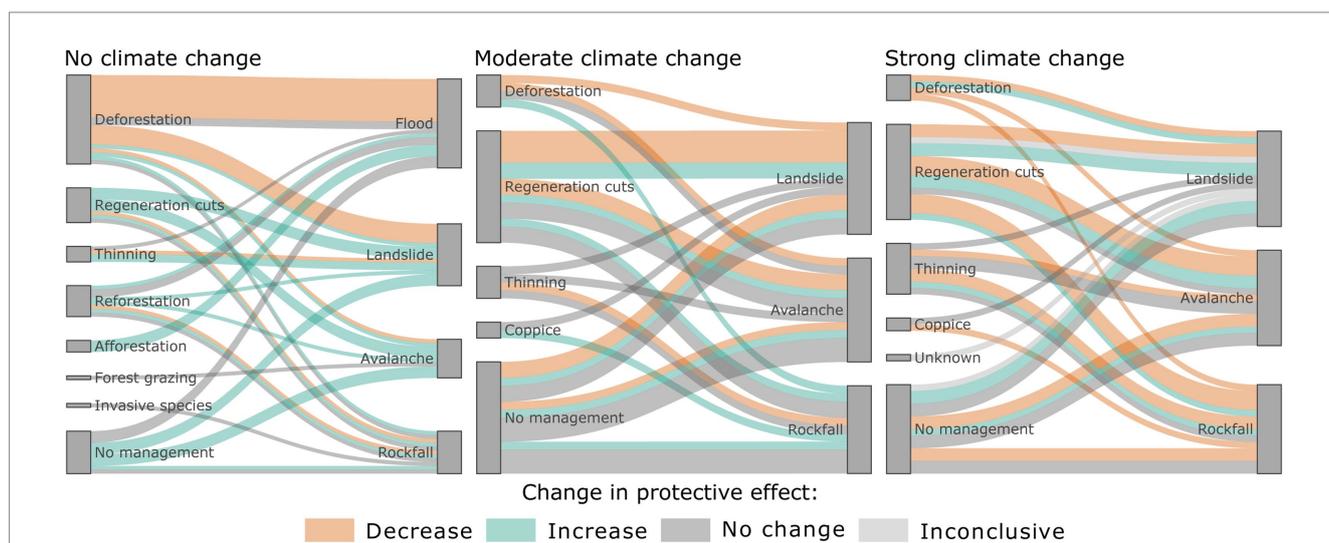


FIGURE 9 Impacts of anthropogenic forest change (left side of the panels) on the protective effect against different types of natural hazards (right side of the panels), under different climate change scenarios (no, moderate, and strong climate change). Specific management interventions were grouped into macro-categories, such as “thinning” or “regeneration cuts.” The width of the connections corresponds to the number of studies/scenarios that examined a specific link, where studies examining multiple natural hazards or scenarios are represented multiple times. Moderate climate change includes climate scenarios with a mean air temperature increase of ~1.5–3.5°C and a slight precipitation decrease of ~10–20%. Strong climate change scenarios foresee a mean air temperature increase of ~3.5–6°C and a significant precipitation decrease of ~20–40%.

nature-based solutions (e.g., [Sudmeier-Rieux et al., 2021](#); [Nehren et al., 2023](#)). A closer look at the network of the authors of the reviewed publications shows also a very strong connection of the authors of studies on avalanche, landslide and rockfall protective forests mainly in the European Alps, while flood-related studies are geographically more distributed and their authors less connected ([Supplementary Figure S2](#)).

Only a few studies assessed how treeline shifts affect the protective effect of forests, which is surprising considering the vast amount of literature available on treeline shifts in mountains (e.g., [Smith et al., 2009](#); [Cudlin et al., 2017](#); [Zindros et al., 2020](#)). This may point out a potential limitation of our search protocol or, more likely, suggest that treeline

research has hardly been directly linked to the consequences of treeline shifts for the forest’s protective effect, which was one of the eligibility criteria for the inclusion of a publication in this review. The maintenance and recovery of high-elevation protective forests was a driver of recent treeline research ([Holtmeier and Broll, 2019](#)), but apparently without assessment of the direct impacts on their protective effect.

Many studies assessed potential changes in the protective effect based on protective forest indices (e.g., related to forest cover density or basal area). Only a few studies tried to quantify the effects of changes in the protective forests on the risk for people and infrastructure in terms of avoided costs (e.g., [Farvacque et al., 2019](#);

Stritih et al., 2019; Moos et al., 2021). However, a quantification of the monetary consequences of global change impacts on protective forests would facilitate decisions on financial and organizational resources required to ensure the durability of protective forests (Dorren and Moos, 2021). This is of particular importance when it comes to the question whether additional technical protection measures are required to compensate for potential losses in the protective effect, where a comparison based on cost–benefit analysis can support decision-making (Alves et al., 2016; Onuma and Tsuge, 2018). Besides changes in their capacity to provide protection, the value of the protective service provided by forests can also be affected by changes on the demand side. For example, land-use change in downstream areas can lead to an increase in population or infrastructure exposed to natural hazards (Tran et al., 2010), thus augmenting the value of protective forests. However, this component of risk is often not explicitly considered in studies on forests' protective effect.

4.1. Implications for protective forest management

The reviewed studies on anthropogenic forest changes mostly focused on impacts at the opposite ends of the management and land-use spectrum—deforestation and no management. Deforestation mostly had a negative impact on the protective effect of forests, particularly against floods and landslides (e.g., Munoz-Villers and McDonnell, 2013; De Aguiar et al., 2018; Malek et al., 2018; Hajian et al., 2019). The process of deforestation can initiate complex, non-linear relationships between the biosphere and atmosphere by changing the hydrological conditions of a site (i.e., water storage capacity, interception, or infiltration; Ellison et al., 2012; Lima et al., 2014). This, in turn, can have a cascade of negative effects on ecosystem services, such as protection against floods and landslides (e.g., Du et al., 2016; Lopez-Ramirez et al., 2020).

Interventions such as thinning and regeneration cuts were also examined by the reviewed studies but showed contrasting impacts on the protective effect of forests against natural hazards, not allowing us to draw general conclusions for the future management of protective forests. On the one hand, this highlights the complexity of the effects of different management interventions, interacting with a changing climate, on the protective effect of forests. On the other hand, it also suggests a strong local context dependency that shapes these interactions. Environmental context dependency is a known phenomenon in ecological research, e.g., on drought stress, biodiversity, or ecosystem functioning, where site characteristics may modulate responses depending on the environmental context (e.g., Forrester et al., 2016; Ratcliffe et al., 2017). Reduced management intensity, for example, was found to improve the protective effect of forests by increasing stand basal area; however, the same management may lead to higher predisposition to disturbances and subsequent risks for the protective effect of forests (Mathys et al., 2021, Switzerland). Reduced harvest intensity improved landslide prevention in conifer plantations in Japan (Yamaura et al., 2021). Regeneration cuts were found to have contrasting results on the protective effect of forests in different sites (e.g., negative effect in *Quercus* and *Pinus nigra* mixed forests in the French Alps, Bigot et al., 2009; positive effect in *Picea abies*-dominated forests in western Austria, Irauschek et al., 2017a; negative to non-significant effects in

key forest types and governance settings in the main mountain ranges of central and southern Europe, Mina et al., 2017) but also within the same study area (in mixed broadleaf and conifer forests in western Austria, Irauschek et al., 2017b). Although mountain landscapes have a high level of spatial heterogeneity, this variability is often not explicitly considered in the analyzed studies, making it difficult to draw definite conclusions on the impact of different local factors that may have contributed to variations in forests' protective effect.

Additionally, besides being case-specific, most studies used modeling approaches to investigate the effect of anthropogenic forest changes and climate change scenarios on forests' protective effect. The assumptions used by different models, as well as limitations related to the sometimes not thorough descriptions of the investigated processes, add uncertainties to an already complex system and make generalizations harder. The strong context dependency and uncertainty about changes in protective forests highlights the need for adaptive forest management, where forest managers need to monitor ongoing changes, learn from these observations, and adapt their management accordingly (Innes et al., 2009).

Among different types of management interventions, the reviewed studies were most consistent about the impact of salvage logging. Most studies that addressed salvage logging after natural disturbances identified a detrimental effect on the protective effect of forests against avalanches and rockfall (e.g., Rammig et al., 2007; Wohlgemuth et al., 2017). As natural disturbances become more frequent under climate change, it will be increasingly important to question the common practice of salvage logging, which has a negative effect on many ecosystem services (Leverkus et al., 2021).

In the face of climate change, management strategies such as thinning and the promotion of regeneration have been increasingly recommended to cope with drought, promote resilience and assure the continuity of forests and the ecosystem services they provide (Bottero et al., 2017; Albrich et al., 2020; Zhang et al., 2023). Our review highlights that understanding in which situations these management strategies may have a negative impact on the protective effect of forests is pivotal to improve the sustainable management of protective forests in mountain areas.

4.2. Implications for future research

The scarce empirical evidence of the effects of global change on protective forests demonstrates the need for increasing efforts in the monitoring of protective forests and their protective effect, as well as the collection and provision of high-quality data on global change impacts at different spatial and temporal resolutions (Ruiz-Benito et al., 2020). Understanding the highly context-specific ways in which different aspects of global change affect protective forests requires in-depth analyses at the local scale. This includes, for example, the long-term monitoring of the effects of management interventions and natural disturbances or the retrospective analysis of the development of the forests' protective effect depending on the forest condition (e.g., Rickli et al., 2019). This could include, for example, long-term monitoring plots of forest recovery and the dynamics of the protective effect after natural disturbances and under different (controlled) local conditions (e.g., Winter et al., 2015; Vergani et al., 2017). Such monitoring efforts will help designing and further developing modeling approaches that explicitly address protective forests and the

interacting effects of global change impacts, as for example proposed by Schmid et al. (2023). Local-scale studies currently use a wide range of indicators and methods to measure forests' protective effect (see Figure 5), which limits their comparability and possibility to conduct meta-analyses across sites. Using consistent indicators (e.g., Blattert et al., 2017) to describe protective forest structure and its impacts on hazard frequency, intensity, and risk, would make it easier to identify potential general patterns in protective forest changes across sites.

The growing accessibility of regional and even global datasets will facilitate the investigation of these processes at a larger scale, an area that is currently clearly underrepresented in research. Most of the analyzed studies here were, in fact, restricted to the slope or watershed scale, while regional, national, or even global studies represented a minority or were even completely lacking for flood protective forests (Supplementary Figure S2). Recent advances in large-scale mapping of forest disturbances over time (e.g., Senf and Seidl, 2021) and their effects on forest structure (Stritih et al., 2023) will facilitate assessments of how changing disturbances may alter the protective effect of forests. However, measuring the protective effect of forests using remote sensing data remains a complex and challenging task. Most of the protective forest indices used to link forest structure to the protective effect (see, e.g., Elkin et al., 2013; Irauschek et al., 2017a,b; Pardos et al., 2017) are based on below-canopy structural characteristics, such as stem density and tree diameter, while remote sensing studies more often provide information on canopy cover (e.g., Vacchiano et al., 2016). Recent approaches linking remote sensing data on forest structure with natural hazard simulations (e.g., Bebi et al., 2021; Costa et al., 2021; Sidau et al., 2021) may help bridging the gap between large-scale observations of forest dynamics and local-scale studies on forests' protective effect.

There is a need for scientific data not only on global change impacts on protective forests, but also on their implications for society. Carrying out comprehensive and long-term inventories of natural hazard events and related damages would enable the assessment of the actual effects of global change impacts on protective forests for communities. Additionally, approaches and tools allowing for a risk-based evaluation and prediction of the forest's protective effect in future should be promoted and further developed. Furthermore, there should be a concerted effort to promote and further develop approaches and tools that allow a risk-based evaluation and prediction of the protective effect of forests in the future (e.g., Moos et al., 2018; Stritih et al., 2019; Chabba et al., 2022; Teich et al., 2022b).

A large knowledge gap prevails regarding the impacts of compound events on protective forests. These are a combination of multiple climate-related events, such as a drought event followed by a forest fire and a flood event, resulting in cascading, often very severe impacts (e.g., Kleinman et al., 2019; Bastos et al., 2021). To investigate the risks emerging from such compound events affecting protective forests, integrative approaches that combine different models, datasets, and expertise are necessary, along with applications to real cases (Leonard et al., 2014; Zscheischler and Seneviratne, 2017). Additionally, climate change is likely to affect the frequency and intensity of natural hazard events (Stoffel et al., 2014), which may in turn further influence the protective effect of forests.

5. Conclusion

Our review evinces that the impacts of climate change, increasing natural disturbances, and anthropogenic forest changes on the protective

effect of mountain forests against natural hazards are manifold and complex. Climate-induced changes are expected to increase forests' protective effect at higher elevations but reduce it at lower elevations, while the impacts of anthropogenic changes, including various management interventions, are highly dependent on the local context and on interactions with climate change. Natural disturbances can decrease the protective effect of forests and this impact is further exacerbated by salvage logging. However, forests are likely to recover their protective effect several years to decades following disturbance, depending on disturbance severity and local site conditions. Most research on protective forests under global change is case-study specific and based on simulation modeling, while empirical evidence remains scarce. We therefore conclude that we need (i) increasing monitoring efforts of global change impacts on protective forests at the large scale; (ii) detailed local-scale assessments of interacting and compound effects as well as (iii) risk-based evaluations of changes in the protective effect of forests to support a pro-active and sustainable management of these extremely valuable nature-based solutions.

Author contributions

CM: conceptualization, literature search, literature review, data analysis, visualization, and writing first draft. AS: conceptualization, literature review, visualization, and writing. MT and AB: conceptualization, literature review, and writing and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/ffgc.2023.1223934/full#supplementary-material>

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