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Research article

Mapping the natural disturbance risk to protective forests across the European Alps

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ABSTRACT

Mountain forests play an essential role in protecting people and infrastructure from natural hazards. However, forests are currently experiencing an increasing rate of natural disturbances (including windthrows, bark beetle outbreaks and forest fires) that may jeopardize their capacity to provide this ecosystem service in the future. Here, we mapped the risk to forests' protective service across the European Alps by integrating the risk components of hazard (in this case, the probability of a disturbance occurring), exposure (the proportion of forests that protect people or infrastructure), and vulnerability (the probability that the forests lose their protective structure after a disturbance). We combined satellite-based data on forest disturbances from 1986 to 2020 with data on key forest structural characteristics (cover and height) from spaceborne lidar (GEDI), and used ensemble models to predict disturbance probabilities and post-disturbance forest structure based on topographic and climatic predictors. Wind and bark beetles are dominant natural disturbance agents in the Alps, with a mean annual probability of occurrence of 0.05%, while forest fires were less likely (mean annual probability <0.01%), except in the south-western Alps. After a disturbance, over 40% of forests maintained their protective structure, highlighting the important role of residual living or dead trees. Within 30 years after wind and bark beetle disturbance, 61% of forests were likely to either maintain or recover their protective structure. Vulnerability to fires was higher, with 51% of forest still lacking sufficient protective structure 30 years after fire. Fire vulnerability was especially pronounced at dry sites, which also had a high fire hazard. Combining hazard and vulnerability with the exposure of protective forests we identified 186 Alpine municipalities with a high risk to protective forests due to wind and bark beetles, and 117 with a high fire risk. Mapping the disturbance risk to ecosystem services can help identify priority areas for increasing preparedness and managing forests towards lower susceptibility under an intensifying disturbance regime.

1. Introduction

In mountainous regions, forests can protect settlements, infrastructure, and downstream areas from natural hazards such as landslides, avalanches, floods, and rockfall (Moos et al., 2018; Teich et al., 2022). This ecosystem service is essential for enabling life in mountain areas, and can have an economic value of hundreds of thousands of Euros per hectare (Grêt-Regamey et al., 2013; Moos et al., 2019), often exceeding the economic value of timber production. The importance of protective forests is increasing under climate change, as there is a growing need for nature-based solutions for disaster risk reduction to deal with more frequent extreme events (UNDRR, 2020). At the same time, however, the capacity of forests to provide protection is challenged by the effects of climate change, such as changes in species composition and disturbance regimes (Moos et al., 2023).

Disturbances such as bark beetle outbreaks, fires, and windstorms are becoming more frequent under climate change (McDowell et al., 2020; Seidl et al., 2017). They result in pulses of tree mortality that

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change forest structure, which can impair the capacity of forests to intercept rockfall (Maringer et al., 2016), buffer runoff peaks (Seibert et al., 2010), or prevent avalanches (Caduff et al., 2022) and landslides (Flepp et al., 2021; Vacchiano et al., 2016). A climate-mediated increase in forest disturbances can thus increase the risk of natural hazards for settlements and infrastructure located at lower elevations (Moos et al., 2019; Sebald et al., 2019). However, disturbance impacts can vary strongly in space, modified by topography, site conditions and forest susceptibility (Gliksman et al., 2023; Stritih et al., 2021a; Vacchiano et al., 2016).

The impact of disturbances on ecosystem service provisioning is not only determined by their immediate consequences, but also by the ability of the system to maintain or recover their structure and functioning during and after disturbance. After a disturbance, forests' protective effect can be partially maintained by surviving trees or dead wood (Costa et al., 2021; Teich et al., 2019), and can recover through natural or artificial regeneration (Caduff et al., 2022; Maringer et al., 2016). However, the recovery of mountain forests is often a slow process, with the regenerating tree cohort taking decades to reach sizes that make them effective in protecting against natural hazards (May et al., 2023; Stritih et al., 2023). Consequently, there can be a gap of several years to decades after disturbance where the forest protective effect is impaired (Wohlgemuth et al., 2017).

Understanding the risk that disturbances pose to protective forests is important for management. The risk can potentially be mitigated by reducing the forests' susceptibility to natural disturbances, e.g. increasing the diversity or naturalness of the species composition (Scherrer et al., 2023a, 2023b) and facilitating advanced regeneration (Hlásny et al., 2021; Szwagrzyk et al., 2018), or by implementing alternative protection measures (Maringer et al., 2016; Wohlgemuth et al., 2017). However, such measures can be resource-intensive, so understanding where the risk from natural disturbances is greatest is essential for effectively managing risks (UNISDR, 2015a). Mapping the risk of natural disturbances for ecosystem services can therefore be a useful tool to prioritize areas for risk management (Lecina-Diaz et al., 2021a). To date, integrative risk assessments have been mostly based on expert knowledge (Lecina-Diaz et al., 2021b), and are often conducted at landscape scale (Stritih et al., 2021a). Analyses at a larger spatial scale could facilitate learning from disturbance events across regions with similar environmental conditions, but large-scale and data-driven risk assessments remain rare (Lecina-Diaz et al., 2024; Moos et al., 2023), limiting the potential for proactive risk management and planning at the regional or national level.

Here, we develop a first wall-to-wall map of the risk of losing the protective service of forests due to natural disturbances across the European Alps (105,000 km^2 of forest). To do so, we utilize remote sensing data on wind, bark beetle, and fire disturbances, as well as post-disturbance forest structure, to model disturbance hazard and vulnerability based on factors such as topography and climate. We then analyze how disturbance hazard, forest vulnerability, and exposure of protective forests coincide in space to identify municipalities with a high risk to losing the protective function of forests.

2. Methods

2.1. Study area

The European Alps are a mountain range in Central Europe, spanning parts of France, northern Italy, Switzerland, southern Germany, Austria, and Slovenia, with elevations ranging from near sea-level to 4809 m a.s.

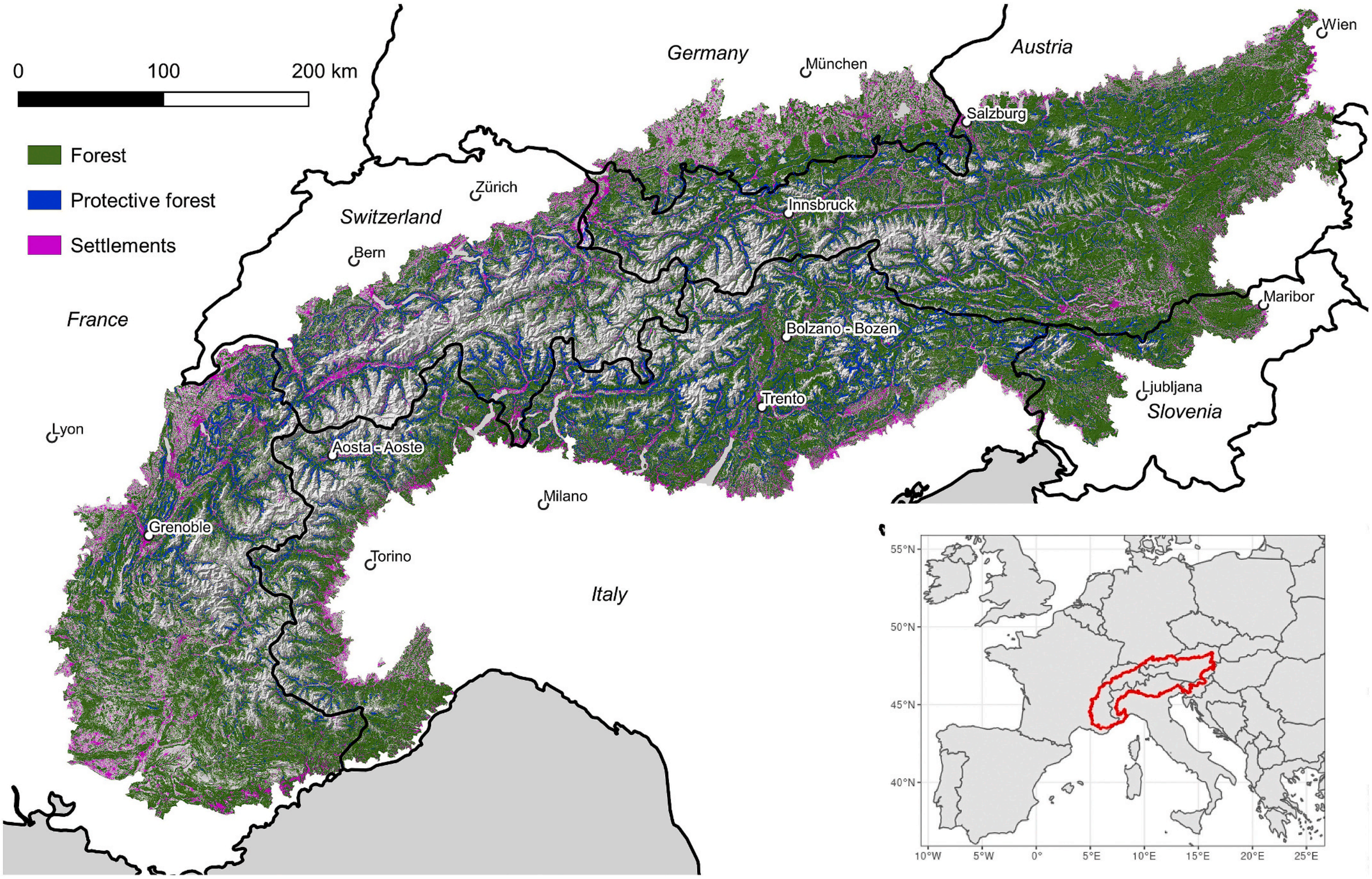


Fig. 1. Map of the study area as defined by the Alpine convention, with the terrain (derived from the Copernicus EU-DEM v1.1, 2016) overlaid with forest cover (Senf and Seidl, 2021a),settlement locations (Schiavina et al., 2022), and locations of protective forests (Schirpke et al., 2019).

l. We considered the extent of the Alps as defined by the Alpine convention, which covers an area of 190,000 km^2 (Fig. 1). The Alps include several climatic zones, from temperate-Atlantic to temperate-continental and from alpine to Mediterranean. Approximately 57% of the Alps are covered by forests, with the upper tree-line between ca. 1800 and 2400 m a.s.l. At lower elevations, forests are dominated by broadleaved trees such as *Fagus sylvatica* L., although past management has largely promoted Norway spruce (*Picea abies* (L.) Karst). At higher elevations, conifers are dominant, including *P. abies*, *Larix decidua* L., and various pine species (mainly *Pinus cembra* L. and *P. mugo* Turra). The European Alps have a population of 14.6 million people (EUROSTAT, 2021) and a relatively high density of infrastructure (including settlements, roads, railways, tourism and energy infrastructure). Particularly in steep valleys, forests thus play a key role in protecting people and infrastructure from natural hazards, such as avalanches, rockfall, and landslides (Teich et al., 2022).

2.2. *Risk assessment*

We assessed the risk to protective forests from natural disturbances by considering three risk components: exposure, hazard, and vulnerability (UNISDR, 2015b; see Fig. 2). Here, exposure corresponds to the ecosystem service of forests protecting people and infrastructure from avalanches and rockfall. We defined hazard as the probability of a disturbance occurring. To assess vulnerability, we evaluated the probability that the forest loses the structure needed to provide protection from natural hazards, where a lower vulnerability reflects the forest's capacity to either maintain or recover their structure after disturbance. We modelled the probability of disturbance and post-disturbance structure empirically based on satellite data, described in more detail below.

2.2.1. *Data on forest disturbances and post-disturbance forest structure*

We modelled disturbance hazard and vulnerability based on two main data sources: a Landsat-based forest disturbance map (Senf and Seidl, 2021a) and data on forest structure from spaceborne lidar (GEDI, Dubayah et al., 2020). The disturbance map provides data on the year of forest disturbances across Europe for the years 1986–2020 at 30m resolution, and differentiates between fire, wind and/or bark beetle, and other disturbances with an overall accuracy of 92% (Senf and Seidl, 2021b). Wind and bark beetle disturbances were considered jointly, since they often occur together (i.e. bark beetle outbreaks following windthrows; Hlásny et al., 2021; Stadelmann et al., 2014), and are thus difficult to differentiate from satellite imagery (Sebald et al., 2021). In the following, we collectively refer to these disturbances as "wind", as wind is the more prevalent disturbance agent in the Alps, e.g. accounting for over 75 % of these disturbances in Austria (Sebald et al., 2021).

GEDI is a satellite-based lidar system designed to measure forest structure, in operation since 2019. It provides waveform data for 25-m diameter footprints, and for each footprint, metrics of vegetation structure (such as canopy cover and percentiles of canopy height) can be derived from the waveform. We used canopy height and cover data as provided by the GEDI level 2A and 2B products from the summer (June–August) of 2019–2021 and filtered the data based on the level 2B product's quality flag, which resulted in a total of 4,380,618 footprints across the European Alps.

In addition to data on disturbances and forest structure, we used data on topography (EU-DEM v1.1, 2016), climate (Karger et al., 2017), wind speed and variability (New European Wind Atlas, 2022), as well as parent material (Panagos, 2006) as predictors for hazard and vulnerability (see Table 1 for a description of all the variables). All the spatial predictors were resampled to 100-m resolution and masked to the forest cover included in the disturbance map (Senf and Seidl, 2021a).

2.2.2. *Hazard: disturbance probability*

We overlaid GEDI footprints with the disturbance map to identify footprints that were disturbed either by wind or by fire, as well as with the environmental predictors. This dataset was used to fit ensemble models predicting the occurrence of wind and fire, with disturbed footprints serving as "presences" and undisturbed footprints as "absences". We focused on site-related drivers of disturbance, since we were interested in the site-specific disturbance risk to protective forests

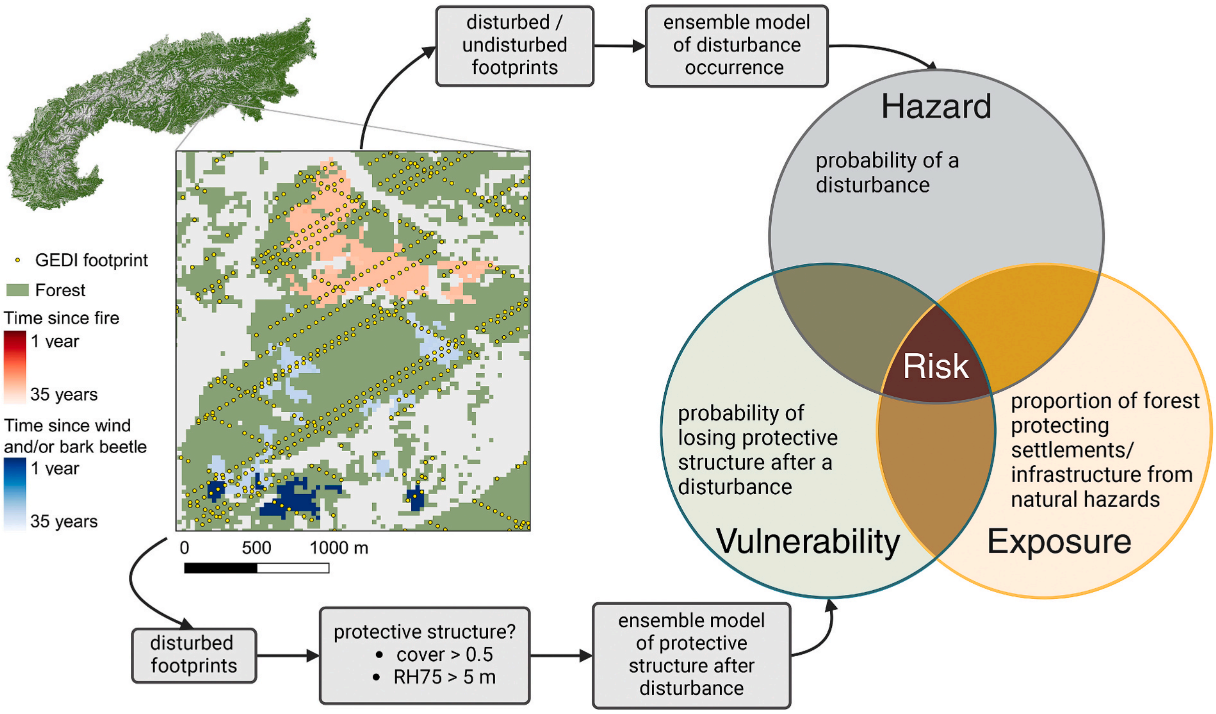


Fig. 2. Definition of risk components and an overview of our approach to derive hazard and vulnerability maps from spatial data. Cover: canopy cover [0–1], RH75: 75th percentile of relative height [m]. Figure created with Biorender.com.

Table 1
Predictor variables used in the models of disturbance hazard and vulnerability.

Predictor	Description	Resolution	Data source
Slope[a]		25 m	EU-DEM v1.1 (2016)
Roughness	Vector ruggedness measure of variability in grid cell directions (Sappington et al., 2007)		
Terrain position	Elevation relative to surrounding cells, from concave (negative values) to convex (positive values) terrain.		
Northerness	Continuous description of aspect: cos(aspect)		
Easterness	sin(aspect)		
Mean annual temperature		1000 m	CHELSA (Karger et al., 2017)
Seasonality	Temperature seasonality		
Precipitation (warmest quarter)	Sum of precipitation during the warmest quarter		
Precipitation (coldest quarter)	Sum of precipitation during the coldest quarter		
Wind speed[b]	Mean wind speed at 50 m height	50 m	New European Wind Atlas (2022)
Wind Weibull-k[b]	Variability of wind speed distribution (higher k indicates lower variability)		
Parent material	Dominant parent material (consolidated-clastic-sedimentary, igneous, metamorphic, sedimentary, unconsolidated deposits, other)	Vector-based	European Soil Database (Panagos, 2006)
Since[c]	Time since disturbance	30 m	Disturbance map (Senf and Seidl, 2021a)

[a] In the vulnerability models, slope was included as a confounding variable in the fitted models, but was not used for predictions to avoid bias related to GEDI data (Mandl et al., 2023).

[b] Predictors were used only for the disturbance probability models and not for the vulnerability models.

[c] Predictor only used for vulnerability models.

irrespective of the current stand conditions.

To predict disturbance probability, we used an ensemble modelling approach with the biomod2 package in R (Thuiller et al., 2023). First, we set aside 10% of the data for model validation, while the remaining 90% were used for calibration. Second, we fitted four types of models, a generalized additive model (GAM), generalized linear model (GLM), gradient boosting model (GBM), and random forest (RF), with 5 runs for each model, and with each run using 80% of the data for model building and 20% for validation. The predicted class membership probabilities from each model in the ensemble were then averaged weighted by model performance, measured using the area under the receiver-operator curve (AUC). The ensemble prediction was finally validated using the 10% of initially set-aside data. Then, we ran projections of the ensemble model on a 100-m raster of the study area (42,470,968 raster cells). Because of the imbalance in the data (many more absences of disturbance than presences), we used weighting to balance the presences and absences in the models. The predicted probabilities were thus centered around 0.5, which we then rescaled to “true” probabilities (Pozzolo et al., 2015) based on overall prevalences of each type of disturbance derived from the disturbance map (see Table 2). An ODMAP protocol (Zurell et al., 2020) of the hazard and vulnerability models is included in the Supplementary material.

Table 2
Performance of the ensemble models, the number of GEDI footprints used in the modelling, the prevalence of “presences”, and the area under the receiver operator curve (AUC), calculated for the 10% of independent testing data, as a measure of model performance. For disturbance hazard, the prevalence is based on the disturbance map, while the prevalence for vulnerability is based on the GEDI footprints.

Model	N presences	N absences	Prevalence [%]	AUC
Wind and bark beetle hazard	84,003	4,219,554	1.9	0.864
Fire hazard	14,348	4,289,268	0.26	0.970
Wind and bark beetle vulnerability	21,014	19,219	52	0.799
Fire vulnerability	7042	2073	77	0.729

2.2.3. *Vulnerability: post-disturbance forest structure*

To model forest vulnerability, we used GEDI footprints that overlapped by >95% with a disturbance patch (where the disturbance occurred before the GEDI measurement), including a 9-m buffer around the footprint to account for possible geolocation errors (Dubayah et al., 2020). We assessed whether these GEDI footprints had a suitable structure for protection against natural hazards based on two structural metrics derived from GEDI data: a canopy cover of >0.5 and a RH75 (75th percentile of relative height) of >5 m. A cover of 50 % and stand height above 5 m are often used as key criteria for the capacity of forests to provide protection against avalanches (Frehner et al., 2005; Perzl and Kleemayr, 2020). RH75 was chosen among other height percentiles because it represents the dominant stand height well, while being less sensitive to artefacts and outliers than higher percentile values (Turubanova et al., 2023).

We modelled the probability that a footprint has lost its protective structure after a disturbance with the same approach as used for disturbance probabilities. In this case, time since disturbance was included as a predictor, and the presences and absences were weighted equally, as the sample was more balanced (see Table 2). To account for the bias of GEDI metrics towards higher values on steeper slopes (Mandl et al., 2023), we controlled for slope in the model and then used a fixed slope value (24°, corresponding to the overall median slope in the study area) in the spatial predictions. We predicted vulnerability for fixed time steps of 1, 15, and 30 years after disturbance.

2.2.4. *Exposure: protective forests*

We used an existing dataset on the ecosystem service of protection from natural hazards by forests in the Alps (Schirpke et al., 2019), which combines information on potential release and transition zones for avalanches and rockfall with data on infrastructure and forest cover. The dataset includes the proportion of forest with a protective role per local administrative unit (LAU; i.e. municipality). Our study area includes 5389 LAUs with an average size of 3551 ha.

2.2.5. *Mapping risk*

We multiplied the modelled hazard (disturbance probability) and vulnerability (probability of losing the protective structure) to map the potential impact of disturbances on forest structure. Here, we assessed vulnerability 15 years after disturbance, since this is when the protective capacity of disturbed forests is expected to be at its lowest, as residual dead wood is decomposing and tree regeneration is not yet sufficient (Caduff et al., 2022; Stritih et al., 2023).

To visualize the spatial patterns of all three risk components (hazard, vulnerability, and exposure), and their interactions, we categorized municipalities across the Alps using a risk matrix. Risk matrices combine semi-quantitative levels of multiple risk components and are commonly used for visualizing risk (Simmons et al., 2017). We categorized each risk component into three levels (low, medium, high) based on equally spaced quantiles, and then combined them. Although such semi-quantitative levels are partly subjective, they can be more readable than continuous maps and allow for comparisons between variables with different distributions (Slocum et al., 2023). Since all combinations of the three components (27 levels) would be difficult to visualize, we reduced the number of categories to six levels, focusing on the interactions between high risk components: (1) low risk (when all risk components have a low value), (2) medium risk, (3) high hazard and vulnerability, (4) high hazard and exposure, (5) high vulnerability and exposure and (6) high risk (high hazard, vulnerability, and exposure).

3. Results

3.1. Disturbance hazard

Across the Alps, 1.9% of forests were disturbed by wind or bark beetles between 1986 and 2020 (average annual disturbance probability of 0.05%), and 0.26% were disturbed by fire (average annual disturbance probability $< 0.01\%$) according to the disturbance map. The fitted ensemble models were able to predict the occurrence of disturbances with AUC values of 0.86 for wind and 0.97 for fire, indicating good model performance (Table 2). Precipitation of the warmest quarter was the most important predictor for both types of disturbance (Fig. 3), with fires being more likely in areas with low summer precipitation (see Supplementary material, Fig. S1). Mean annual temperature, northerness, and slope were also important predictors for both types of disturbance. Wind disturbance was more likely on less steep and south-facing slopes, while fire probability was higher on steep south-facing slopes, and increased with mean annual temperatures above 10 °C.

Overall, the mean annual predicted probability of fires per 100-m grid cell was 0.0021%. The predictions had a right-skewed distribution, with 95% of the predicted probabilities between 0.0002% and 0.01% (Fig. 4). Fires were most likely in the south-western part of the Alps, near the Mediterranean, along the southern edge of the Alps, and in some central Alpine valleys (Fig. 5). The predicted probability of wind disturbance was higher (mean = 0.04%, 95% of predictions between 0.01% and 0.09%) and less variable in space, with similar probabilities across most of the central and eastern Alps, and lower probabilities in the western Alps (Fig. 5).

3.2. Vulnerability

The vulnerability models had a lower performance than the hazard models, with AUC values of 0.80 and 0.73 for wind and fire, respectively. After wind disturbance, there was a 56% probability of losing the forests' protective structure one year after disturbance (Fig. 4), and the predicted vulnerability remained similar 15 years after disturbance. Time since disturbance and mean annual temperature were important predictors for the protective structure after wind disturbance, with vulnerability decreasing rapidly after >15 years since disturbance, especially in areas with higher temperatures. 30 years after wind disturbance, there was a 61% probability of the forest having a sufficient protective structure. Forests were least vulnerable to wind in the south-eastern and north-western Alps, while forests at higher elevations were

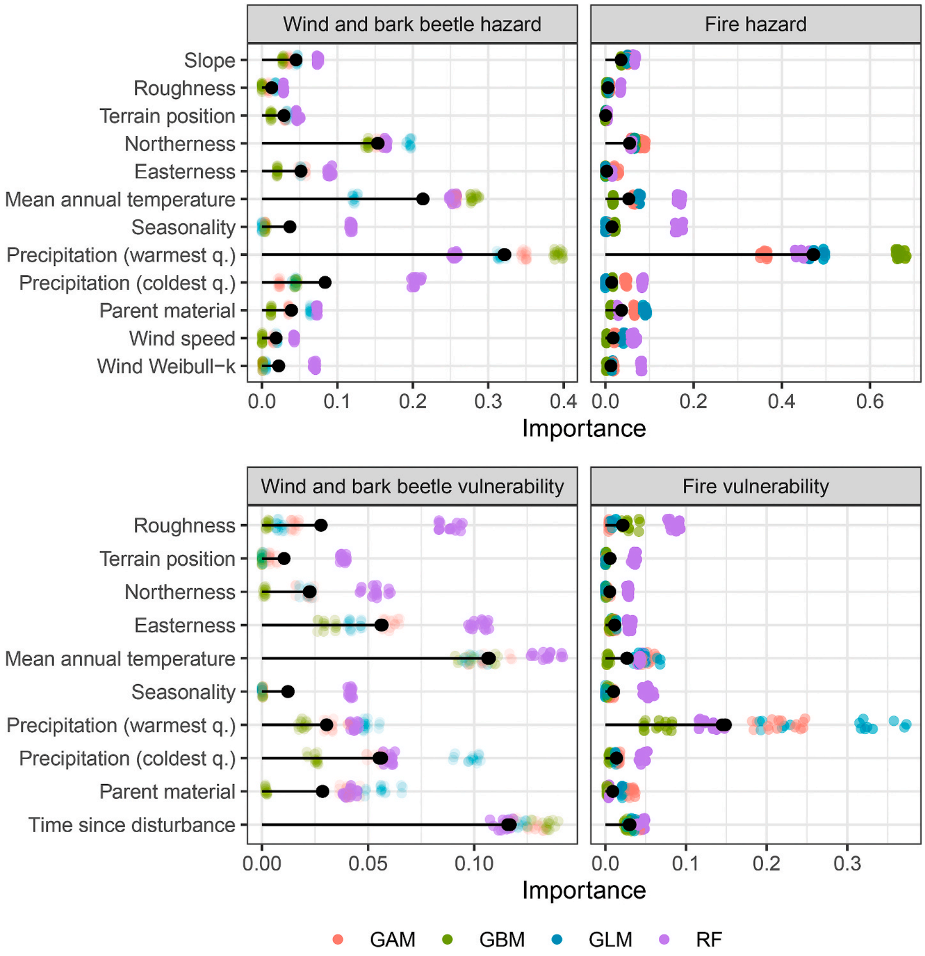


Fig. 3. Variable importances in the ensemble models predicting wind and fire hazard and vulnerability. Variable importance is calculated by randomizing each variable and comparing model predictions with original and randomized values (importance = 1 – correlation of original and randomized predictions) (Thuiller et al., 2023). Colored dots show importances in individual model runs (GAM: generalized additive model, GLM: generalized linear model, GBM: gradient boosting model, RF: random forest). The level of transparency indicates model performance (AUC), while the black line and dot indicate the importance in the model ensemble.

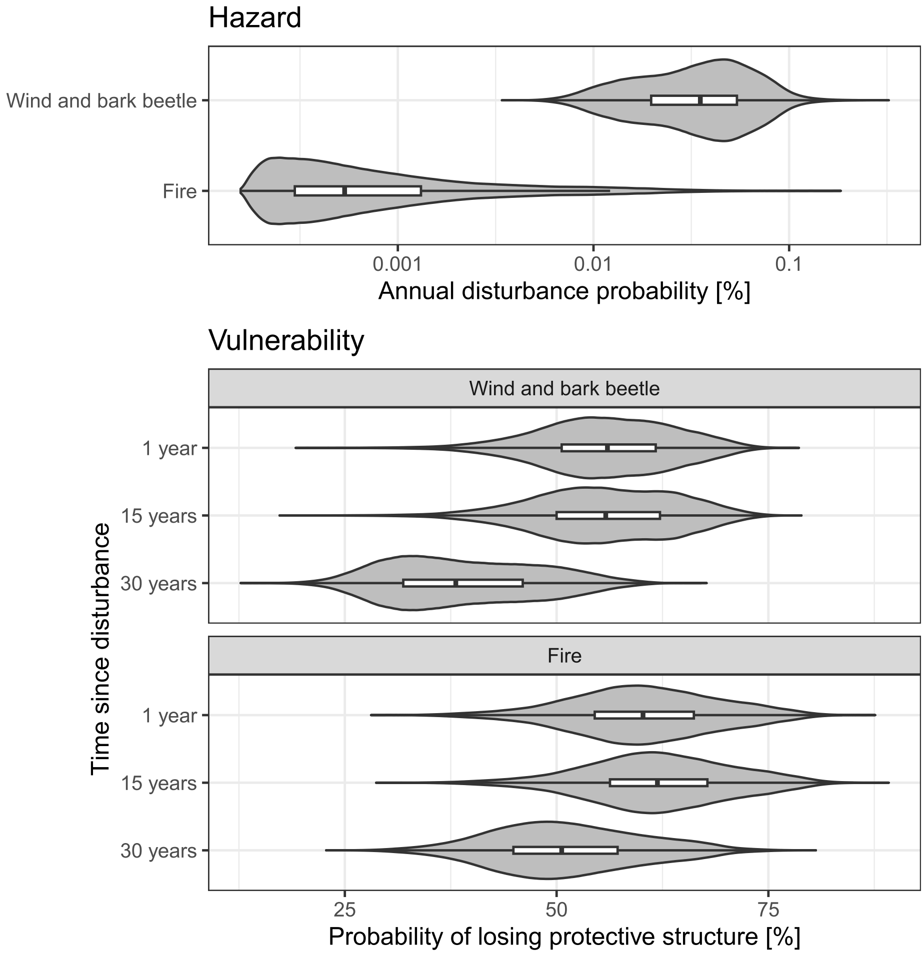


Fig. 4. Distributions of predicted probabilities of disturbance hazard and vulnerability. Hazard probabilities are shown on a log scale for better visibility.

generally more vulnerable than low-elevation forests (Fig. 5).

Vulnerability to fire showed a different pattern, with the highest vulnerability in the south-western Alps. The most important predictor for vulnerability to fire was the precipitation of the warmest quarter, with areas with low precipitation showing higher vulnerability. The mean predicted probability of losing the protective structure 15 years after fire was 62%, which decreased to 51% after 30 years (see Fig. 4 and Supplementary material, Fig. S6).

3.3. Disturbance risk

Broadscale patterns in the potential impact of disturbances mostly reflected the spatial variability in disturbance hazard, since the hazard was more variable in space than vulnerability (see Fig. 5). Among the 5389 LAUs in the Alps, 490 had high levels of wind disturbance hazard and vulnerability. However, most of these areas are in lower elevations and outside of LAUs with a high proportion of protective forests (i.e. have low-medium exposed values; see Fig. 6). When considering all three risk components, only 186 LAUs (3.5%) fall into the high-risk category, mainly in northern Italy (see Fig. 6), Austria, and Switzerland. Together, these municipalities have a population of over 340,000 people (EUROSTAT, 2021), and include many prominent ski resorts, such as Cortina d'Ampezzo, Adelboden, and Schladming.

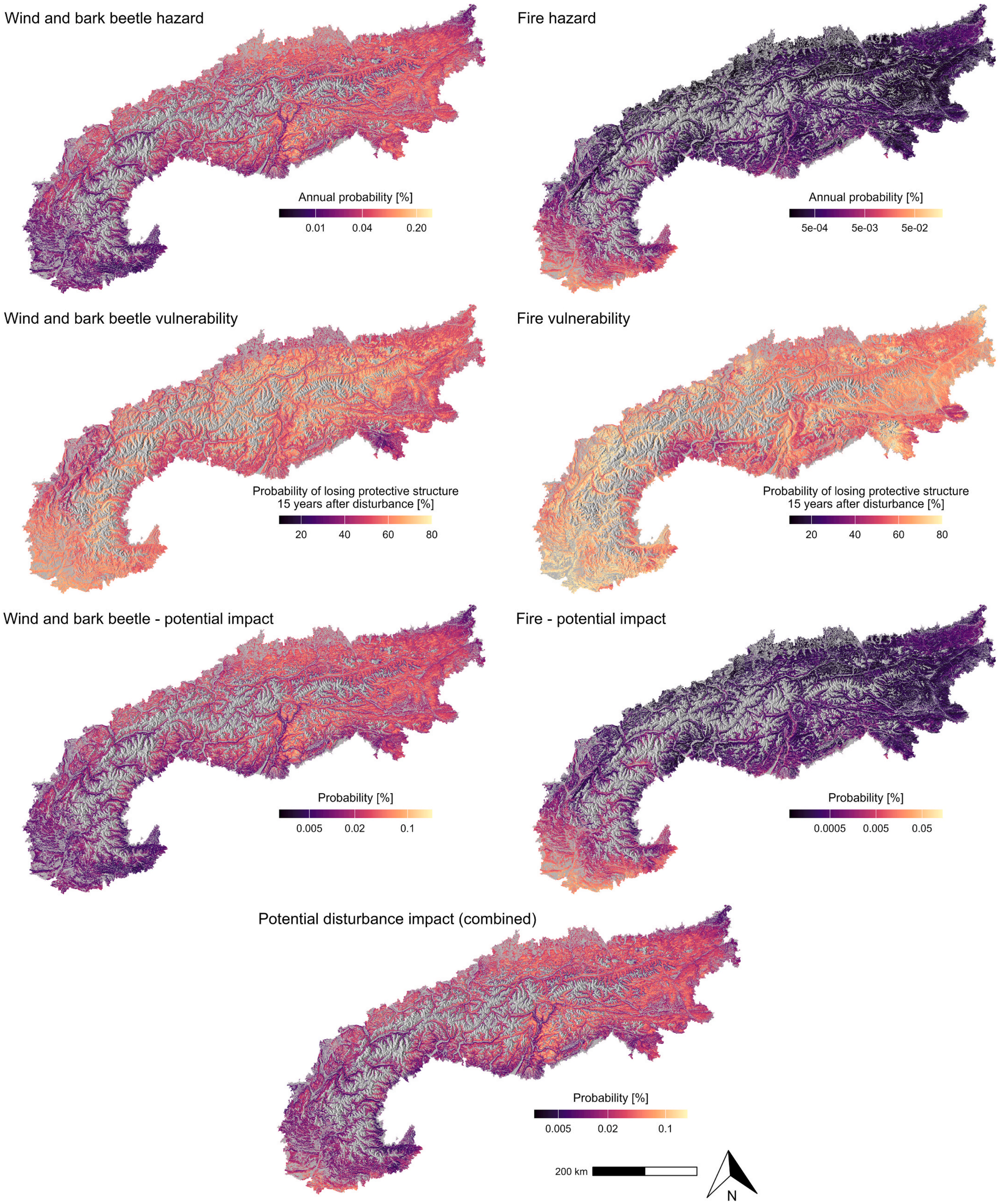
In case of fire, there is a larger overlap between areas of high fire probability and high probability of losing the forest's protective structure after fire, which means that 996 LAUs have a high level of both hazard and vulnerability. However, these LAUs are mostly in the western Alps, where the proportion of forests providing protection for infrastructure or settlements is lower. Therefore, only 117 (2%) of LAUs were categorized to have high fire risk, with a total population of almost 170,000. This includes municipalities in the French Alps, the Rhone valley in Switzerland and Aosta valley in Italy. There are no LAUs that were identified as high risk for both wind and fire disturbances.

4. Discussion

4.1. Spatial variability in disturbance hazard and vulnerability

Disturbance hazard is variable across the European Alps, driven by strong climatic gradients at the regional scale as well as local-scale topographic variability. Our models were able to predict fire occurrence with high accuracy (Table 2), suggesting that fire hazard is closely linked to topographic and climatic predictors (Grünig et al., 2023). Model performance was slightly lower for wind and bark beetle, suggesting a higher importance of drivers not explicitly included in our model. In previous studies, the occurrence of these disturbances has been closely linked to species composition (Stadelmann et al., 2014) and management legacies (Stritih et al., 2021b). In particular, wind and bark beetle disturbances have been linked to the promotion of Norway spruce in sites where it would not dominate naturally (Scherrer et al., 2023b), including lower elevations and warm and dry sites, such as those where our models predict a high wind hazard.

At the regional scale, we found a clear distinction between areas predominantly affected by wind and fire, confirming the strong separation between disturbances by fire and wind disturbances previously reported at the continental scale in Europe (Senf and Seidl, 2021b). Windstorms and bark beetle outbreaks were dominant drivers of natural disturbance in most of the Alps (Bebi et al., 2017), while fires mostly



Wind and bark beetle hazard

Fire hazard

Wind and bark beetle vulnerability

Fire vulnerability

Wind and bark beetle - potential impact

Fire - potential impact

Potential disturbance impact (combined)

Fig. 5. Ensemble predictions of wind and fire hazard and vulnerability (probability of losing the forest's protective structure 15 years after disturbance). The potential impact is a combination of hazard and vulnerability. The bottom map shows the combined probability (sum) of both types of disturbance impacts.

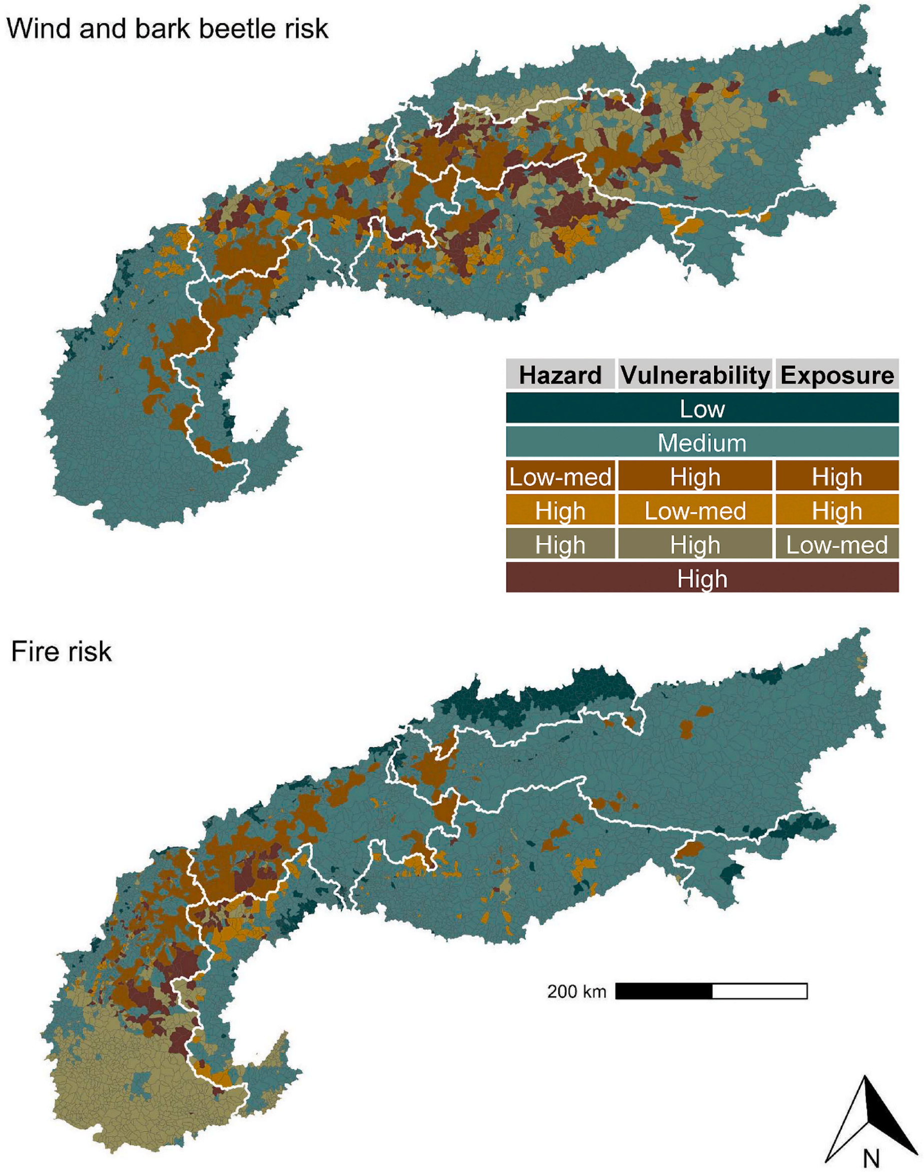


Fig. 6. Combination of risk components for wind and fire disturbances. © EuroGeographics for the administrative boundaries.

occurred in the submediterranean, south-western part of the Alps. However, this separation may become less clear in the future, as higher temperatures and aridity will increase the likelihood of large and severe fires throughout Europe (Grünig et al., 2023). Together with an expected increase in lightning frequency (Chen et al., 2021) and fuel accumulation due to land abandonment in mountain areas (Mantero et al., 2020), the fire hazard is likely to increase across the Alps in the future.

We were able to predict vulnerability with moderate accuracy (Table 2), even though post-disturbance forest structure is affected by several interacting processes, such as forest recovery, management (e.g. salvage logging and tree planting), and ungulate browsing (Rammig et al., 2007). We found that over 40% of forests maintained a structure suitable for providing protection from natural hazards even immediately after disturbance. This reflects the small patch sizes (Maroschek et al., 2023; Stritih et al., 2024) and intermediate severity of natural disturbances in the Alps (Stritih et al., 2023). Surviving trees as well as downed or standing deadwood can maintain the protective effect during the first years after disturbance (Caduff et al., 2022; Costa et al., 2021; Teich et al., 2019). At the same time, deadwood facilitates forest recovery, as it can retain moisture and help maintain suitable microclimatic conditions for seedling establishment (Bottero et al., 2013; Mantero et al., 2024). However, salvage logging after disturbances is still a common practice in the Alps, even though it can exacerbate disturbance impacts on ecosystem services (Leverkus et al., 2018; Moos et al., 2023).

Although wind disturbances were more likely to occur than fires, fires were more likely to impair the protective effect of forests over longer periods, as forests are less likely to maintain or recover their structure after fire than after wind disturbance. Vulnerability to wind and fire were also associated with different drivers, with lower temperatures limiting recovery after wind, and low precipitation limiting recovery after fires. Fires are more likely to damage the soil seed bank (Mantero et al., 2024), as well as any advance regeneration, and a loss of understory vegetation further exposes seedlings to drought (Harvey et al., 2016). Most of the dominant conifer species in the Alps do not have strong adaptations to fire, although broadleaves such as downy oak and beech can resprout (Pausas et al., 2016), especially after low to moderate severity fires (Moris et al., 2023). The vulnerability of forests in drier parts of the Alps to fires means that these areas are particularly likely to experience long-term shifts towards alternative vegetation states in a warming climate, such as low and open-canopy forests or shrubland (Seidl and Turner, 2022; Stritih et al., 2023). Such shifts could mean a permanent reduction of the protective effect, as open forests have a lower capacity to prevent or mitigate natural hazards (Frehner et al., 2005).

4.2. Managing disturbance risks

Mapping the disturbance risk to protective forests can help identify priority areas for management. For example, in areas of high risk, it may be important to prepare for implementing alternative protection measures in the event of forest disturbances, such as rockfall nets (Maringer et al., 2016) or avalanche barriers (Wohlgemuth et al., 2017). Measures to facilitate forest recovery after disturbances, such as targeted tree planting (Mantero et al., 2024), should be prioritized in areas with high disturbance vulnerability and exposure. In contrast, lower priority should be given to forests with low vulnerability, which are likely to maintain or recover their protective function even without management interventions (Seidl et al., 2019), as well as forests that do not have a critical protective role (i.e. low exposure), where a prolonged recovery after disturbance may be acceptable.

Here, we identified broad-scale patterns in disturbance risk based on site-related factors, such as climate and topography. However, on the local scale, the risk of natural disturbances also depends on stand-level factors, such as forest structure, species composition, or land-use legacies, which modify the susceptibility of forests to disturbances (Stritih et al., 2021b). The prioritization of risk reduction measures will also depend on the level of demand for protection from natural hazards. We used a map of protective forests that does not differentiate between different types of infrastructure that the forest is protecting (Schirpke et al., 2019). However, the value of protective forests can be highly variable, depending on the number of people and the value of infrastructure exposed to damage from natural hazards (Moos et al., 2019; Stritih et al., 2019). Risk reduction measures therefore need to be tailored to local conditions, with broad-scale mapping such as the one presented here only being the first step of an effective risk management. Furthermore, as predictions of disturbance risk are uncertain, forest management should aim to foster resilience even in forests where the anticipated risk is relatively low (Seidl, 2014).

4.3. Limitations and outlook

In this study, we used a space-for-time approach to assess forests' vulnerability to disturbances over time after disturbance. By assessing the forests' horizontal and vertical structure using GEDI, we were able to evaluate the capacity of the forest to provide protection from natural hazards. However, this approach does not allow us to distinguish different trajectories of post-disturbance development, such as whether a specific area maintained its structure after a disturbance (i.e. had a high degree of resistance), or whether it initially lost its protective structure and then recovered. Furthermore, we do not have information about the pre-disturbance forest structure, which means that some forests may have already had an open or low canopy structure before disturbance (Stritih et al., 2023). Given the relatively small changes in vulnerability over time after disturbance, especially during the first 15 years, our results suggest that vulnerability is mostly driven by the initial resistance to disturbance, rather than by recovery. However, investigating specific post-disturbance trajectories and differentiating between resistance and recovery would require time series of forest development, such as those provided by optical satellite imagery (Mandl et al., 2024). At the same time, optical imagery is limited in its capacity to capture changes in vertical forest structure (Bolton et al., 2017), making it less suitable to assess the development of protective forests, where stand height is critical for their capacity to provide protection (Frehner et al., 2005). In the future, a higher availability of repeated lidar or photogrammetric surveys will likely facilitate a better understanding of protective forest dynamics (Baggio et al., 2022; Krüger et al., 2024).

We used a broad definition of protective forests, including protection against various types of natural hazards (Schirpke et al., 2019), and applied general indicators of forest structure (cover and height) as proxies for forests' protective capacity (Mandl et al., 2023). We note, however, that different structural and compositional characteristics could be important for specific natural hazards. For example, stem density above a certain threshold diameter is critical for protection against rockfall (Frehner et al., 2005), while the size of gaps and species composition influence the effect of forests on avalanche formation (Schneebeli and Bebi, 2004). Such structural characteristics can be derived from airborne lidar at the landscape scale (Baggio et al., 2022; Costa et al., 2021), but are not yet available at the scale of the entire European Alps.

This study focused on protection from natural hazards as a key ecosystem service in mountain regions, but our risk analysis approach could be extended to other ecosystem services, such as carbon storage, timber production, recreation, or habitats of valued species (Pártl et al., 2017; Stritih et al., 2021a). In this context, it is important to consider that different ecosystem services respond differently to natural disturbances. For example, disturbances can cause a loss of stored carbon (Pugh et al., 2019), but they often have ambiguous impacts on recreation and positive impacts on biodiversity (Kortmann et al., 2021; Thom and Seidl, 2016). We here focused on an ecosystem service where disturbances have immediate detrimental effects, but note that long-term effects of disturbances on ecosystem service provisioning can be more variable. Disturbances can, for instance, help restore a more natural species composition in forests with strong management legacies (Dollinger et al., 2023) and accelerate forest adaptation to climate change (Scherrer et al., 2021; Thom et al., 2017). In the long term, disturbances can thus even strengthen the protective effect of forests (Scheidl et al., 2020).

5. Conclusions

Intensifying natural disturbance regimes can jeopardize the capacity of mountain forests to provide protection against natural hazards. Here we show that this risk is highly spatially heterogeneous across the European Alps, and is strongly contingent on the type of disturbance. Across the Alps, forests have a relatively high capacity to maintain or recover their protective structure after disturbances. Disturbance legacies, such as surviving trees and deadwood, often maintain the protective effect after a disturbance, which should be considered in the management of disturbed areas. Wind and bark beetle disturbances are the dominant natural disturbance agents across large parts of the Alps, but fires exert a stronger negative effect on the protective function of forests where they occur. Post-fire recovery is especially limited at dry sites and in the south-western Alps, where the protective effect of forests is thus particularly sensitive to the expected further increases in disturbance frequency and size. However, areas of high fire hazard and vulnerability do currently not coincide with a high demand for protection from natural hazard, thus reducing the overall risk for protective forests. This demonstrates the need to jointly consider hazards, vulnerability, and exposure to prioritize areas for risk management under global change.

CRediT authorship contribution statement

Ana Stritih: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cornelius Senf:** Writing – review & editing, Data curation, Conceptualization. **Thomas Marsoner:** Writing – review & editing, Data curation. **Rupert Seidl:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the data used in this study is openly available. The code used for data processing as well as the output maps are available at: https://zenodo.org/doi/10.5281/zenodo.12684178

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.121659.

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