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Addressing disturbance risk to mountain forest ecosystem services

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ABSTRACT

Ecosystem service (ES) mapping has been developed with the aim of supporting ecosystem management, but ES maps often lack information about uncertainty and risk, which is essential for decision-making. In this paper, we use a risk-based approach to map ES in mountain forests, which are experiencing an increasing rate of natural disturbances, such as windthrow, bark beetle outbreaks, and forest fires. These disturbances affect the capacity of forests to provide essential ecosystem services, such as protection from natural hazards, wood production, and carbon sequestration, thus posing a challenge for forest management. At the same time, disturbances may also have a positive effect on certain services, e.g. by improving habitats for species that rely on dead wood. We integrate forests' susceptibility to natural disturbances into probabilistic Bayesian Network models of a set of ES (avalanche protection, carbon sequestration, recreation, habitats, and wood production), which combine information from remote sensing, social media and in-situ data, existing process-based models, and local expert knowledge. We use these models to map the level of the services and the associated uncertainties under scenarios with and without natural disturbances in two case study areas in the Swiss Alps. We use clustering to identify bundles of risk to ES, and compare the patterns of risk between the non-protected area of Davos and the strictly protected area of the Swiss National park with its surroundings. The spatially heterogeneous pattern of risk to ES reflects topographic variability and the forest characteristics that drive disturbance susceptibility, but also the demand for ecosystem services. In the landscape of Davos, the most relevant risks to ES are related to decreases in the protection against avalanches and carbon sequestration, as well as some risk to wood production and recreation. In the strictly protected Swiss National Park, the overall level of ES risk is lower, with an increase in habitat quality under the disturbance scenario. This risk-based approach can help identify stands with high levels of ES that are particularly susceptible to disturbances, as well as forests with a more stable ES provision, which can help define priorities in forest management planning.

1. Introduction

Ecosystems globally are undergoing change at an unprecedented rate (IPBES, 2019; IPCC, 2018), exposing many of the ecosystem services (ES) they provide to risks related to changes in land use (Foley et al., 2005), climate, and an increasing frequency of extreme events (IPCC, 2014). This challenges the provision of services that are essential for human well-being (IPBES, 2019), and generates a high level of uncertainty for ecosystem managers (Polasky et al., 2011).

Mountain ecosystems provide essential ES to both local and global populations (Grêt-Regamey and Weibel, 2020), but are also sentinels of climate change (Pepin et al., 2015) and particularly vulnerable to extreme events (Klein et al., 2019). In the Alps, mountain forests provide crucial protection from natural hazards (such as avalanches, rockfall, and landslides), as well as storing carbon, providing timber and energy resources, places for recreation, and habitats for rare and charismatic species, which are valued by a wider society (Schirpke et al., 2019). In recent years, the dynamics and management of Alpine forests have been increasingly driven by natural disturbances, such as windthrow, bark beetle outbreaks, and forest fires (Seidl et al., 2014b; Usbeck et al., 2010), and these events are expected to become more frequent due to climate change (Anderegg et al., 2020; Yu et al., 2019). Disturbances can

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transform forests from carbon sinks into carbon sources (Anderegg et al., 2020; Pugh et al., 2019) and contribute to an unstable provision of timber and energy (Albrich et al., 2018). In addition, disturbances can affect forests' capacity to provide protection from natural hazards (Sebald et al., 2019; Vacchiano et al., 2016), and affect landscape aesthetics (Sheppard and Picard, 2006) and recreational value (Flint et al., 2012). At the same time, disturbances can also have a positive effect on biodiversity (Thom and Seidl, 2016). The expected intensifying disturbance regime will thus pose important new challenges for forest managers (Kulakowski et al., 2017; Nikinmaa et al., 2020), and the degree to which forest managers should interfere in the forests' natural disturbance regime is increasingly disputed (Müller et al., 2019; Thorn et al., 2020). Combining information about disturbance risk with ES assessment could therefore help to identify priority areas for intervention or non-intervention and support forest management decisions (Lecina-Diaz et al., 2021; Seidl et al., 2018).

In other fields that deal with high levels of uncertainty, such as finance or hazard management, the concept of risk is routinely used to inform decisions under uncertainty by combining impacts with probabilities (Dow et al., 2013). In modern portfolio theory, risk is calculated by multiplying asset returns with their variance (Alvarez et al., 2017) and allows for portfolio managers to optimize their returns under uncertainty. This approach has been translated to ES, for example to investigate optimal strategies for forest owners under a payments for ES scheme (Matthies et al., 2015). However, since not all ES values can be expressed in monetary terms, it is often difficult to compare measures of returns for different types of ES (Alvarez et al., 2017). In addition, the portfolio manager for whom to optimize is not always clearly defined, especially in case of public goods, making it challenging to implement portfolio management for ES.

In hazard management, risk is defined by the probability and the impact of hazards, and described as a function of the magnitude of an extreme event (hazard), the value of assets that are subject to potential losses (exposure), and the probability that a hazard will cause damage to an asset (vulnerability) (UNISDR, 2015). Assessments of risk can provide a basis for decisions about acceptable vs. intolerable levels of risk (Dow et al., 2013). However, although the ES framework has been developed with the aim of supporting decision-makers (Daily et al., 2009), risk is rarely explicitly addressed in ES assessments (Dong et al., 2018; Hein et al., 2015). Recently, Lecina-Diaz et al. (2021) combined forest fire hazard, susceptibility, adaptive capacity, and ES supply to map risks in Catalonia, while Pártl et al. (2017) combined information on various hazards with ES provision to identify hotspots of ES risk in Czechia. Attempts have also been made to include risks to ES supply in ecological risk assessments in China (Dong et al., 2018; Xu et al., 2016). However, the level of risk to ES depends on their value to people, which is determined not only by the potential supply of ES, but also by the demand for ES. The local demand for ES can be influenced by specific management regimes, such as protected areas. Protected areas affect the level of ES provision (Hanna et al., 2020; Mina et al., 2017), as well as the demand for and access to ES (Schirpke et al., 2020). For example, publicity and information provided to visitors in protected areas can affect people's choices (Millhäusler et al., 2016) and perception of the landscape (Backhaus et al., 2013; Crouzat et al., in review). To provide information about risks to ES that is relevant for decision-makers, it is therefore important to include information about the demand for ES (Mandle et al., 2020).

Mapping ES supply and demand has been used to support ecosystem management and landscape planning by identifying hotspots and trade-offs or synergies between different ES that consistently occur together (i.e. "bundles") (Raudsepp-Hearne et al., 2010; Saidi and Spray, 2018; Tallis and Polasky, 2009). However, maps of ES are often created at a broad spatial scale, which does not correspond to the scale relevant for applications in ecosystem management (Spake et al., 2017). Many ES mapping approaches are based on coarse ecosystem categories such as land cover (Eigenbrod et al., 2010), neglecting the spatial structure within these categories (Spake et al., 2017; Sutherland et al., 2016), although characteristics such as forest type or stand age can have an important effect on ES (Yamaura et al., 2021). The increasing availability of remote sensing can facilitate more detailed ES assessments (Cord et al., 2017), but ES assessments are still associated with high uncertainties related to data, models, and the inherent variability of ecosystems (Stritih et al., 2019; Willcock et al., 2020).

Bayesian Networks (BNs) are an increasingly popular tool to model ES (Gonzalez-Redin et al., 2016; Smith et al., 2018) due to their capacity to integrate both quantitative and qualitative information (such as expert knowledge), and to explicitly address uncertainties (Kelly (Letcher) et al., 2013). The probabilistic structure of BNs is particularly well suited for modelling systems with high levels of uncertainty, and for risk assessments (Grêt-Regamey and Straub, 2006; Kleemann et al., 2017; McDonald et al., 2016), where it is important to consider not only the most likely outcomes, but also extreme events. BNs have thus been used for risk-based evaluations of ES under future scenarios (Grêt-Regamey et al., 2013a), to assess uncertainties in ES assessments (Smith et al., 2018), and to disentangle different sources of uncertainty (Stritih et al., 2019). Therefore, BNs also have the potential to evaluate specific risks to ES, such as forest disturbances, while taking into account their interactions with other uncertainties in ES assessments.

In this study, we assess the spatially explicit risks to mountain forest ES due to natural disturbances and compare the risks to ES between the non-protected landscape of Davos and the strictly protected Swiss National Park with its surrounding. To model a set of mountain forest ES, we use BNs that combine different types of information about ES supply and demand, and integrate the associated uncertainties. These probabilistic models are used to map the ES under scenarios with and without natural disturbances to identify areas where the ES may be particularly at risk due to disturbance. In addition, we use clustering to identify bundles of ES risk and discuss how these could be used to identify management priorities.

2. Methods

2.1. Case study areas

We assessed the risk to forest ES due to natural disturbances (windthrow, bark beetle outbreaks, forest fires, avalanches, and snow breakage) in two case study areas in the south-eastern part of the Swiss Alps, the tourism resort of Davos and the Swiss National Park (SNP) with its surroundings (see Fig. 1). The town of Davos is a well-developed urban and touristic centre, located in the central part of the main valley at an elevation of 1550 m a.s.l.. The rest of the main valley and the three side valleys in the region are relatively rural, with a few scattered settlements and a landscape still strongly dominated by mountain agriculture. Overall, the case study area of Davos covers an area of 254 km^2 and an elevation range from 1250 to 3146 m a.s.l.

The region of the lower Engadin and Val Müstair has a similar topography to Davos, with elevations from 1019 to 3410 m a.s.l. and a traditional agricultural landscape characterized by historic villages and the steep-flowing river Inn. The region includes the SNP, which was established in 1914 as the first national park in the Alps and the only national park in Switzerland. The park is designated as a category Ia nature reserve (highest protection level - strict nature reserve, IUCN), which means that all human interventions are excluded. Visitors are not allowed to leave the hiking trails, and the park is closed in winter. Today, the park covers an area of 170 km^2 and forms the core zone of the UNESCO Biosphere Reserve Engiadina Val Müstair, which also includes the regional nature park Biosfera Val Müstair and a part of the municipality of Scuol.

In both regions, most of the forests are conifer-dominated, and the treeline occurs between 2100 and 2400 m a.s.l.. In these mountainous areas, one of the most important ES provided by forests is protection from natural hazards, such as avalanches (Grêt-Regamey et al., 2008).

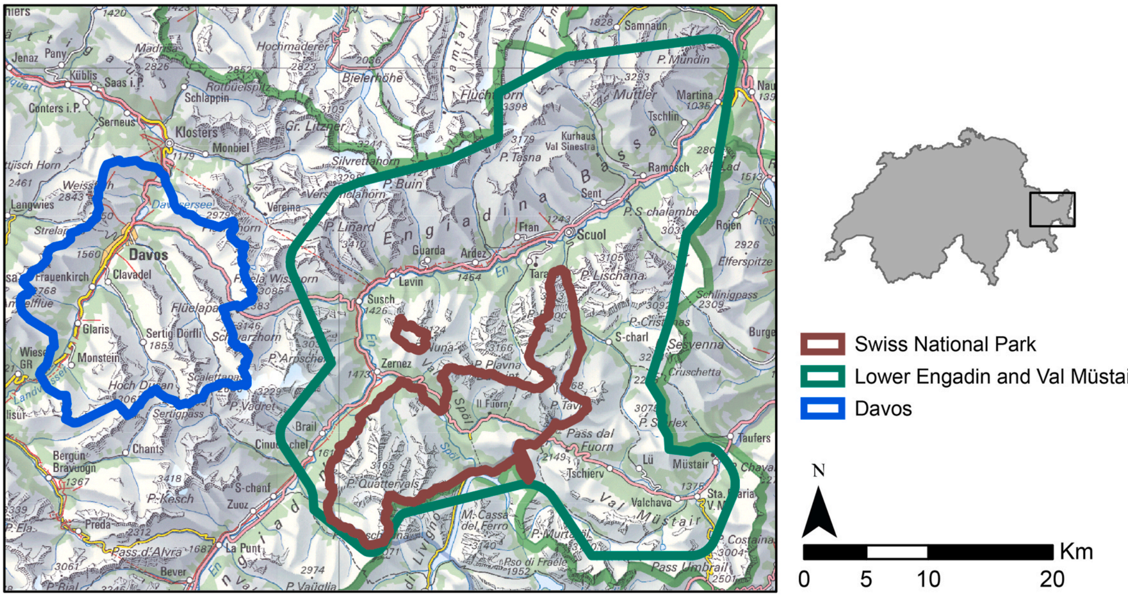

Fig. 1. Overview of the case study areas (National topographic map 1:500′000, swisstopo).

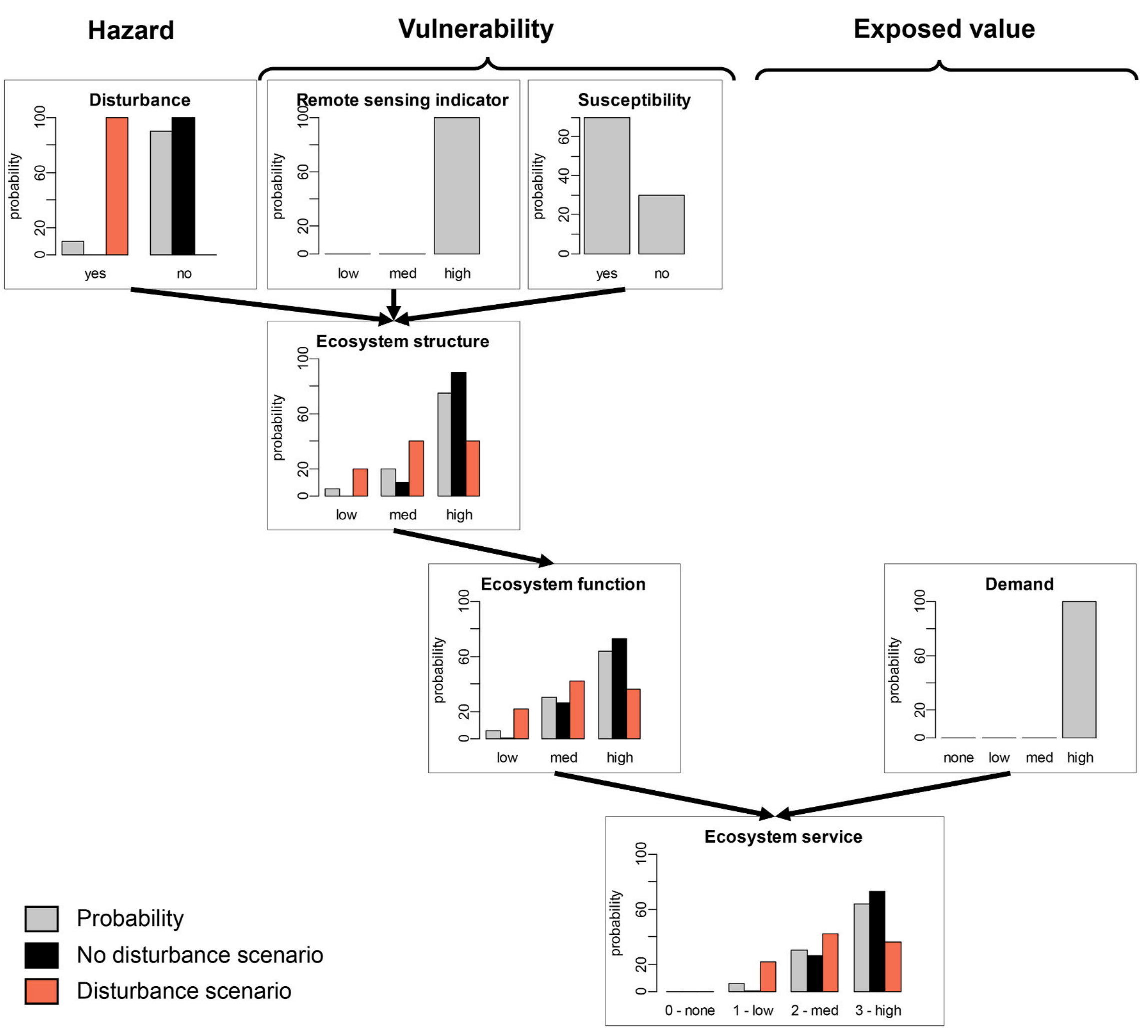

Fig. 2. Conceptual representation of a Bayesian Network of an ecosystem service, where each box shows a node with its probability distribution over possible states. Evidence has been set for the nodes “Remote sensing indicator”, “Demand”, and “Susceptibility”, where the evidence for susceptibility is based on probabilities derived from modelling of natural disturbances in the region (Stritih et al., 2021). For the other nodes, the overall posterior probability distribution as well as the probability distributions under disturbance and no-disturbance scenarios are shown.

Most forest management outside the park takes place in the form of small-scale interventions, such as selective cutting, shelterwood felling, and thinning (Temperli et al., 2017), and a large part of downed wood is salvaged after disturbances. Due to the difficult mountainous terrain, timber extraction often requires cable yarding or helicopter, and wood production is currently not profitable in most forests in the region. Most of the forest management interventions are primarily aimed at maintaining the forests' protection capacity (AWN, 2018a) and are subsidized by the cantonal and federal governments. In addition, biodiversity is recognized as a priority in national policy (FOEN, 2012) and local forest managers aim to maintain habitats for priority species such as capercaillie (AWN, 2018). Moreover, recreation is an important ecosystem service in Davos (Grêt-Regamey and Kytzia, 2007), the SNP and the surrounding region (Backhaus et al., 2013; Crouzat et al., in review).

2.2. Assessing risk with Bayesian Networks

We use a risk-based approach with BNs to assess ES and the risk to ES due to natural disturbances. BNs are graphical models that consist of nodes representing variables and links representing dependencies between nodes (Jensen, 2001; Kjaerulff and Madsen, 2013). Each node has a finite set of possible states (qualitative states such as land cover, or discretized quantitative states such as canopy height). The links between nodes are quantified in conditional probability tables, which contain the probability distribution of the "child" nodes for each combination of states of its "parent" nodes.

The BN models of ES combine information about ecosystem structure and function, demand for ecosystem services, and disturbance effects (see conceptual representation in Fig. 2), while taking into account the uncertainty in each component (Stritih et al., 2019). Since each conditional probability table in the network can be defined individually, the BN models can integrate different types of information, e.g. by "learning" from data, process-based models, or expert knowledge (Borsuk et al., 2004). To combine quantitative (e.g. tonnes of carbon) and qualitative variables (e.g. landscape attractiveness), all of the final ecosystem service values were expressed in four levels (no service, low, medium, high level). For quantitative variables, the discretization into levels was defined based on quantiles of the mean predicted value.

When we run the BNs with spatially explicit evidence, the output consists of a probability distribution of the ES for each pixel of the study area. We summarize the probability distribution by calculating the expected value $E[X] = \sum_{i=0}^{N} p_i \cdot i$, where i represents the index of the state (0 - no service, 1 - low, 2 - medium, 3 - high level of ES) and p_i is the probability of state i (Landuyt et al., 2015). This calculation of expected value takes into account the probability and level of ES value, analogous to risk-based calculations of asset values in modern portfolio theory (Alvarez et al., 2017; Matthies et al., 2015).

The risk-based calculation of expected value takes into account the overall uncertainty related to ES, which includes the chance of natural disturbances, but also other sources of uncertainty, such as data and model uncertainty, epistemic uncertainty in expert knowledge, as well as natural variability. To extract only the risk related to natural disturbances, we therefore calculate the specific disturbance risk as $Risk(dist) = E[ES_{dist.}] - E[ES_{no\ dist.}]$, where $E[ES_{no\ dist.}]$ is the expected value of ES under a scenario without disturbances and $E[ES_{dist.}]$ is the expected value under a disturbance scenario (see Fig. 2). Negative values indicate a loss of ES, while positive values indicate an improvement in ES. This calculation of risk integrates the *vulnerability* of a forest to disturbances (including its susceptibility and the probability that ES will be affected by the disturbance) as well as the *exposed value* of ES (see Fig. 2).

2.3. Exposed values – ecosystem services

We modelled five ecosystem services: carbon sequestration, wood production, avalanche protection, recreation, and habitats. The models of ES were based on remote sensing inputs as proxies of ecosystem structure, including a classification of vegetation types derived from Sentinel-2 images (European Space Agency, 2016, see details in Appendix A), and a canopy height model (Ginzler and Hobi, 2015), as well as a digital terrain model (swissALTI3D, swisstopo, 2015). Ecosystem structure was linked to ecosystem functions and services based on process-based models and in-situ data (for carbon sequestration, wood production, and avalanche protection, see Table 1), and based on literature and expert knowledge (for recreation and habitats). Below, we briefly describe the individual ES models, while the details of all the models are shown in the Supplementary material (Appendix B). We used the BN software Netica to develop the models (Norsys, 2010), and then ran the BN models spatially at a 100m-resolutionusing gBay, an online tool for BNs with geodata (Stritih et al., 2020). The 100-m cell size corresponds to the grid of available species observation data used for validation, and results in a model run for each of 157680 raster cells for the area of the SNP and lower Engadin, and 39856 cells for Davos.

For *carbon sequestration*, in-situ data from the cantonal forest inventory of Graubünden (AWN, 2018b) were used to "learn" the relationship between canopy height and the stock of aboveground biomass, and to estimate forest growth rates based on site and stand characteristics. The growth rates were also used to estimate the amount of wood available for *wood production* (Grêt-Regamey et al., 2013a), and its value was calculated based on wood prices and harvesting costs. The model for *avalanche protection* was based on the BN described in Stritih et al. (2019), where forests can prevent avalanche releases and have a braking effect on avalanche flows, while the demand for avalanche protection is

Table 1
Summary of ecosystem service models, with type of models used and the data used as inputs (RS indicates the remote sensing inputs). The details of each model are provided in Appendix B.

Ecosystem service	Model type	Input data
Carbon sequestration and Wood production	Process-based	RS: vegetation type, crown cover, canopy height Land-use history (historical maps) Elevation, slope (DTM, swissALTI3D) Dead wood amount Distance to roads (swissTLM3D, swisstopo, 2020) Protected area Harvesting costs, wood prices
Avalanche protection	Process-based	RS: vegetation type, crown cover, gap width Elevation, slope, curvature, terrain roughness (DTM, swissALTI3D) Dead wood Buildings, roads, protection barriers (swissTLM3D) Process-based avalanche simulations Snow height distribution
Habitats	Literature-based	RS: vegetation type, crown cover, canopy height Neighbourhood forest cover Distance to forest cover, distance to grazing area Land-use history Dead wood Elevation, slope (DTM, swissALTI3D) Distance to roads, road density, hiking paths (swissTLM3D) Protected area
Recreation	Expert-based	RS: crown cover Points of interest (OSM, 2020) Viewshed of mountain peaks Accessibility: roads, ski lifts, hiking paths, bus stops (swissTLM3D)

determined by the infrastructure and people at risk.

Recreation was modelled based on the accessibility and landscape attractiveness, where the most important factors determining the attractiveness of the landscape for recreation (topography and view, places of cultural importance, and wildlife observation potential) were determined by experts from the SNP and tourism organizations from the surrounding communities (Crouzat et al., in review). The spatial pattern of recreation was validated using the locations of the Flickr pictures as a proxy for the actual use of recreation areas (Langemeyer et al., 2018; Wood et al., 2013).

We modelled the *Habitats* of three regionally important species: capercaillie (*Tetrao urogallus* L.), an indicator species for structurally diverse mountain forests (Suter et al., 2002), the three-toed woodpecker (*Picoides tridactylus* L.), a keystone species in forests with substantial amounts of dead wood (Bütler et al., 2004; Roberge and Angelstam, 2006), and red deer (*Cervus elaphus* L.), a charismatic species that attracts visitors to the SNP (Millhäusler et al., 2016). The models for each species were based on existing literature from the region and validated using observation data (Info fauna, 2018; Vogelwarte, 2018, see Table 2), and the final value of habitats combined all three species' habitats with an OR-operator (e.g. if an area is highly suitable for any of the species, the level of the habitat service is high).

2.4. Vulnerability to natural disturbances

Each ES model includes the potential effects of natural disturbances on the service, where the prior probability of a disturbance is estimated based on overall natural disturbance rates in the region (Stritih et al., 2021). The probability that a specific stand is affected by a disturbance is additionally determined by its susceptibility, which is affected by site and stand characteristics, management, and land-use history (Stritih et al., 2021). The severity of a disturbance is expressed through a probability distribution of tree mortality, which is estimated based on forest management records. Mortality and the decay of dead woody debris affect carbon sequestration levels, while salvage logging after disturbances influences both the amount of harvest and the types of wood products. Reduced forest cover and new gaps created by disturbances can limit forests' avalanche protection capacity, although this can be partly mitigated by snags and downed dead wood (Teich et al., 2019; Wohlgemuth et al., 2017). A higher amount of dead wood improves habitat suitability for the three-toed woodpecker, but may have a small negative effect on the perceived landscape attractiveness (Rewitzer et al., 2017).

2.5. Identifying bundles of ES risk

To summarize the information about risk related to different ES and identify areas with similar levels of risk (i.e., bundles of risk), we performed a cluster analysis on all the forest pixels in the study areas using the cluster package in R (version 2.1.1, Maechler et al., 2021; R Core Team, 2019). First, the most suitable number of clusters was identified using a bootstrapped calculation of the gap statistic (Tibshirani et al., 2001), and then clustering was performed with the k-medoids algorithm, a robust alternative to k-means (Kaufman and Rousseeuw, 1990).

Table 2
Validation of the expert- and literature-based models for habitats and recreation. The AUC (area under the receiver operating curve) is a measure of model performance, calculated as the area under the curve of true positives (presences) vs. false positives (random absence points) at different thresholds of presence probability. AUC values above 0.8 indicate good model performance.

Model		AUC	Validation data
Habitats	Three-toed woodpecker	0.849	Observation data (Vogelwarte, 2018)
	Red deer	0.815	Observation data (Info fauna, 2018) and grazing damage (forest management data, AWN, 2019)
	Capercaillie	0.877	Forest management plan – capercaillie habitat (AWN, 2018a)
Recreation		0.852	Flickr photo locations

3. Results

The maps of ES value (Fig. 3) show a high level of spatial heterogeneity within mountain forests, as well as differences between both study areas. The spatial pattern of the expected value of carbon sequestration mainly reflects forest structure, with larger stocks of wood and higher growth rates in favourable growing conditions at lower elevations, such as in the Lower Engadin valley. The potential for wood production is closely linked to carbon sequestration, while the probability of realizing the potential harvest is limited by accessibility in some remote locations. In most of the forests, harvesting is carried out using a cable system, and high harvesting costs lead to a low value of wood production, with low spatial variability. Inside the SNP, no harvesting is allowed, so the wood production value is zero (Fig. 3).

Most of the forests in both regions are suitable habitats for at least one of the modelled species, and slightly more suitable inside the national park due to the lower level of anthropogenic disturbance. In contrast, the spatial patterns of recreation and avalanche protection are largely driven by demand. The expected value of recreation is mainly determined by accessibility, with higher values near towns and roads, and a lower value in more remote areas. In the SNP, recreation is limited to hiking paths, as visitors are not allowed to leave the trails. Inside the park, there are some forests important for avalanche protection above the main road crossing the park, but overall, the demand for avalanche protection is low. The value of avalanche protection is higher outside the park, particularly on the slopes above towns and villages (Fig. 3). The forests with the highest avalanche protection value are dense evergreen forests on steep slopes, which would have a high probability of avalanche releases in case there was no forest.

Most of the modelled ES show a decrease in expected value under the disturbance scenario (Fig. 4). The risk of a loss of ES is largest for carbon sequestration, and there is a correlation between the expected value of the service and the associated risk (see correlations in Appendix, Table C1). However, at high levels of carbon sequestration, there is a wide variability of risk, which reflects differences in forests' susceptibility to natural disturbances. At higher elevations and in open forests, the susceptibility to disturbances is lower. In addition, salvage logging is not common in inaccessible areas and absent in the SNP, and the dead wood remaining in these stands decays slowly, meaning that the immediate loss of carbon stored in these ecosystems is low in comparison to forests at lower elevations. For avalanche protection, we also find a clear correlation between the expected value of the service and risk due to disturbances, where forests that provide more avalanche protection are also more susceptible to disturbances. The risk for avalanche protection is mostly lower in the SNP and higher outside the park.

For the other modelled ES, the magnitude of changes in the expected value of ES under the disturbance scenario is lower (Fig. 4). The risk for wood production is correlated with risk for carbon sequestration (see Appendix, Table C2), but not clearly related to the expected value of wood production. While the volume of wood production would increase on the short term in case of disturbance due to salvage logging, the lower prices of salvaged wood result in a lower value of wood production in most areas. However, since the expected value of wood production is already low under the disturbance scenario, this change is small (Fig. 4). The expected value of habitats shows small increase under the disturbance scenario, related to the increased availability of dead wood, which is particularly important for the three-toed woodpecker. This increase is more likely in the SNP, where no salvage logging takes place, while the risk to habitats is close to zero in most areas outside the park. The increase in habitat suitability in the park contributes to a higher probability of wildlife sightings and thus a small increase in the expected value

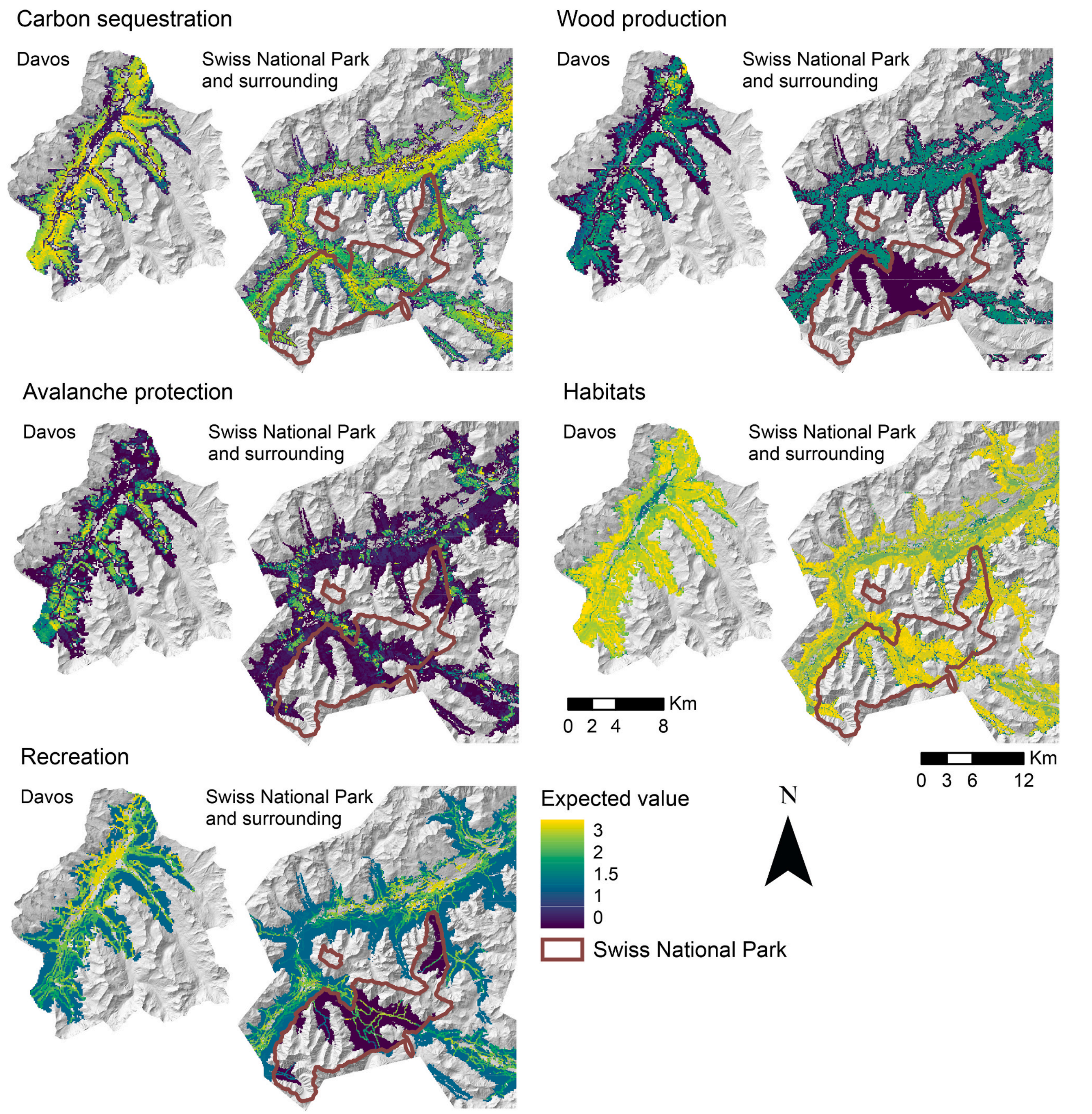

Fig. 3. Map of the expected value of five ecosystem services in the area of Davos and the Swiss National Park with the surrounding lower Engadin and Val Müstair.

of recreation under the disturbance scenario. Outside the park, disturbances have a small negative impact on the attractiveness of the landscape for recreation.

The cluster analysis identified 6 main clusters of ES risks (see Fig. 5). Clusters 1–3 represent areas where multiple forest ES are at risk due to disturbances. In cluster 1, carbon sequestration, wood production and avalanche protection may all decrease under a disturbance scenario, while a small increase in habitat quality can be expected. This cluster is mainly located in dense forests on avalanche-prone slopes above towns and roads. Cluster 2 includes areas with some risk to recreation, mostly near towns and recreational infrastructure. Forests with lower risk to avalanche protection and carbon sequestration are included in cluster 3, which is most widespread on the north-facing slope of the Lower Engadin valley (north of the SNP, see Fig. 5). Cluster 4, with the largest improvement in habitats and a low risk for carbon sequestration and avalanche protection, is mostly found within the SNP, as well as in some forests outside the park, particularly in remote locations in the lower Engadin. Cluster 5 represents areas with a low risk to carbon sequestration and small improvement in habitats, mostly in more remote areas and in the national park, while cluster 6 includes areas near the treeline with low risk to all modelled ES.

4. Discussion

4.1. Natural disturbance effects on ecosystem services

The increasing rate of natural disturbances is likely to affect ES in mountain forests, but their effect is heterogeneous in space and across

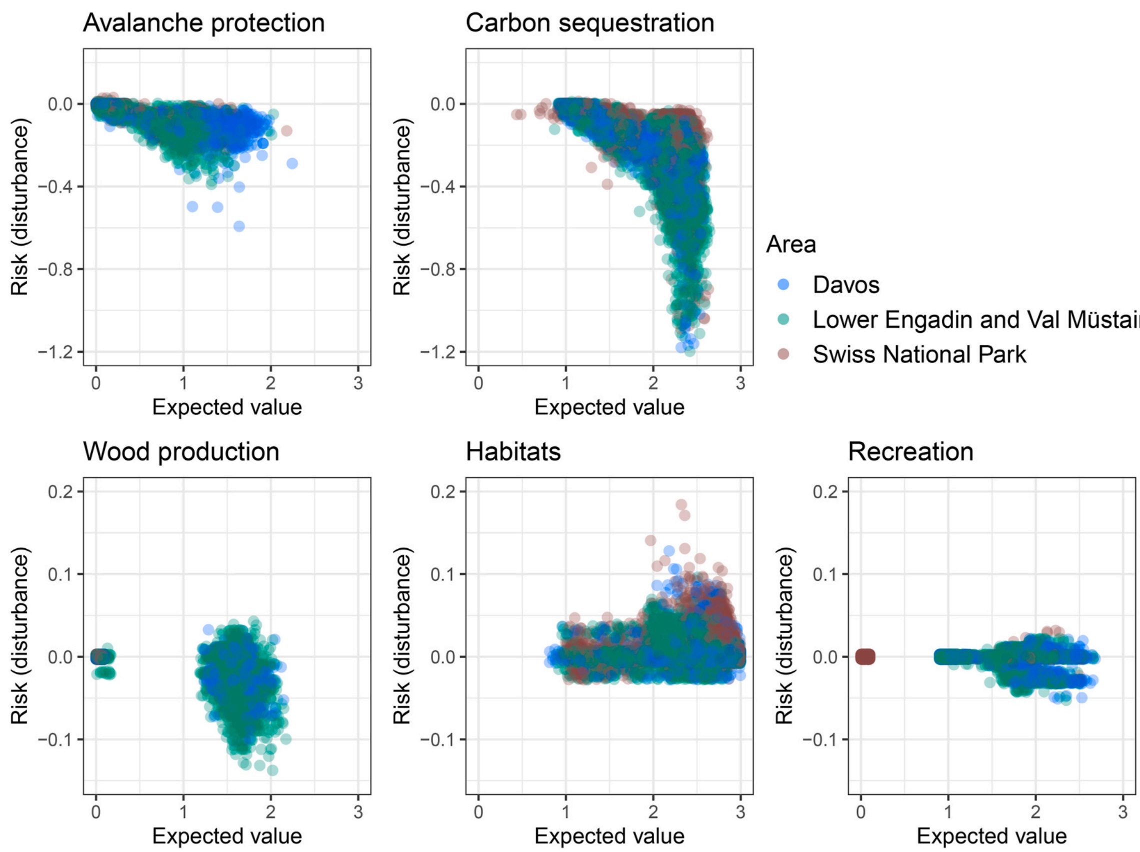

Fig. 4. Risk to ES due to natural disturbances (i.e. difference between expected value in disturbance and no-disturbance scenario) vs. expected value for different ES. Points represent forested pixels, and expected values are categorized from 0 (no ES) to 3 (high ES value). To reduce overplotting, a subsample of 20% of the pixels is shown.

different types of ES. In part, the disturbance impact is driven by factors that determine forests' susceptibility to disturbances, such as topography, stand structure and land use history (Stritih et al., 2021). However, it also depends on the way that disturbed forests are managed and perceived by people.

Natural disturbances and the extent of salvage logging after such disturbances affects all of the modelled ES. In this study, we assumed that some salvage logging takes places in most accessible forests outside the SNP, which results in a clear distinction of disturbance effects inside and outside of the national park. Salvage logging is a common practice in forest management, aimed at utilizing at least part of the wood of dead or damaged trees before they decay and mitigating the risk of subsequent bark beetle outbreaks (Müller et al., 2019). However, the quality of wood is often lower compared to regular harvests, and the profitability of salvage logging is low, particularly in areas with high harvesting costs such as the Swiss Alps (Temperli et al., 2017). On the other hand, when dead wood remains in the stand after disturbances, it provides important habitats for the three-toed woodpecker as modelled in this study, but also for many other birds, plants, insects, and fungi (Thorn et al., 2020). In dry, inner-alpine valleys and at high elevations, such as in the SNP, the slow decomposition of woody debris (Vanderhoof et al., 2013) may buffer the loss of carbon after disturbances, although dead wood decay and thus long-term effects on ES are associated with high levels of uncertainty (Schmid et al., 2016).

Besides supporting biodiversity, dead wood can also contribute to maintaining forests' capacity to protect from natural hazards, such as avalanches or rockfall after disturbances (Teich et al., 2019; Wohlgemuth et al., 2017). The effect of dead wood for maintaining avalanche protection is likely to play an important role in the future, as our results indicate that areas with a high value for avalanche protection also have a high probability of a loss of ES due to disturbances. Some of the structural characteristics that support avalanche protection (i.e. dense evergreen stands) also make forests more susceptible to natural disturbances, indicating a trade-off between the current protection effect and the long-term stability of protection forests (Temperli et al., 2020).

Our results indicate a small negative effect of forest disturbances on the attractiveness of the landscape for recreation, in line with previous studies (Flint et al., 2012; Rewitzer et al., 2017; Ribe, 2009; Sheppard and Picard, 2006; Thom and Seidl, 2016). However, this effect is weaker in the SNP. A survey carried out in the park in the 1990s showed that some visitors expressed a negative perception of dead wood in the park, as it was perceived as "untidy" (Hunziker, 1997). However, due to the park management's effort to inform visitors about the ecological importance of dead wood, as well as changing visitor demographics, a repeated survey found that visitors perceived dead wood as neutral or even positive (Backhaus et al., 2013). This example demonstrates that the risk to ES due to natural disturbances is partly shaped by people's perceptions.

Here, we modelled the short-term effects of natural disturbances, which are the currently the most visible effect of climate change in mountain forests (Kulakowski et al., 2017). However, on the long-term, climate change is likely to have other effects on mountain forests, such as an upward shift in the treeline, which may lead to an increase in carbon sequestration and avalanche protection (Grêt-Regamey et al., 2013b). On a longer time scale, feedback loops between management and disturbances are important for the long-term provision of ES. For example, the long-term protection capacity of forests after disturbances will depend on the speed of regeneration, which in turn may be influenced by the intensity of ungulate browsing (Brüllhardt et al., 2015; Wohlgemuth et al., 2017). While forest management interventions can increase disturbance susceptibility on the short term (Stritih et al., 2021), interventions that increase species- and structural diversity may

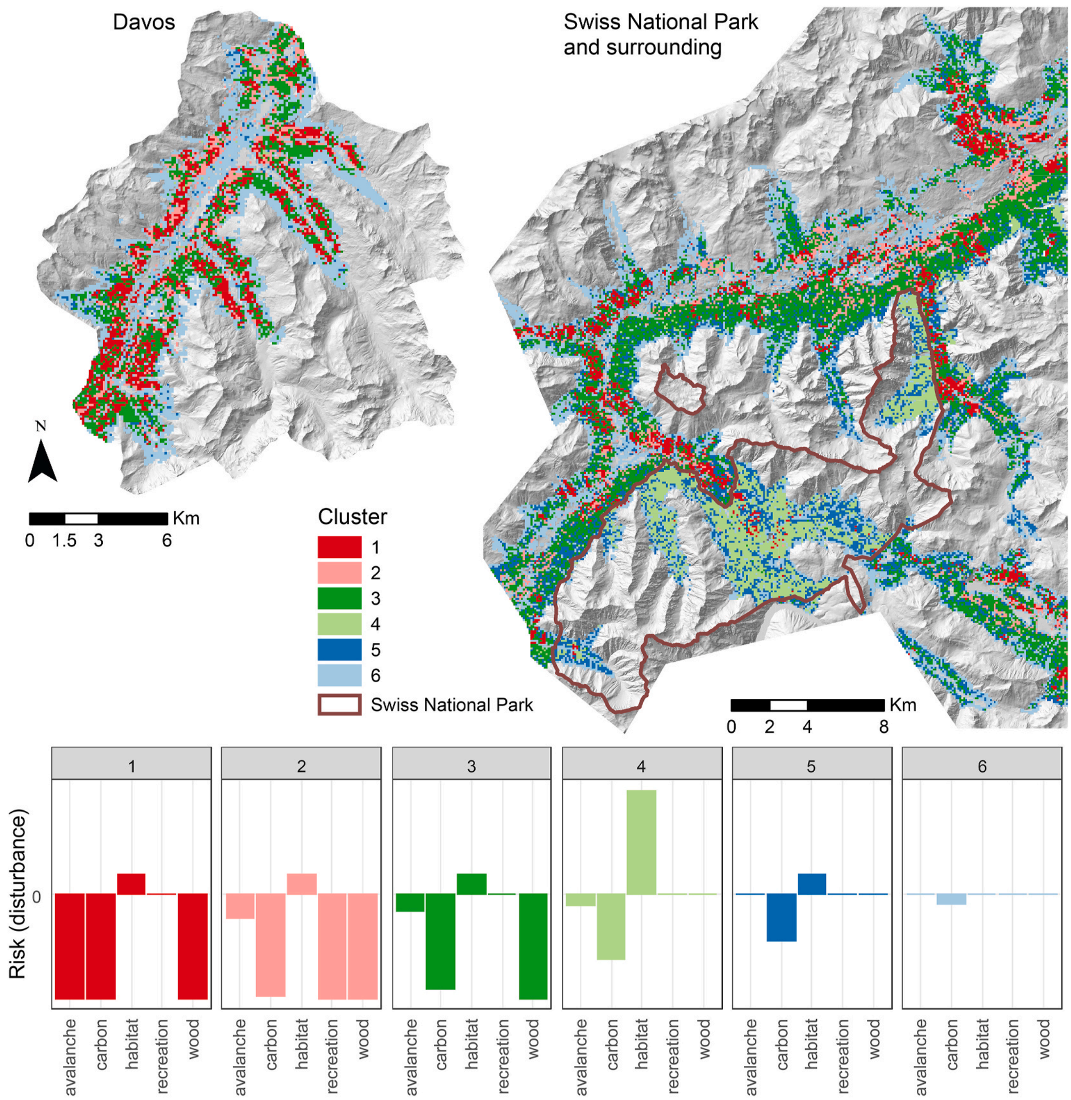

Fig. 5. Map of the clusters based on risk to ES, and their characteristics, where the bar height indicates the median risk for each ES (avalanche protection, carbon sequestration, habitats, recreation, wood production) due to disturbances (scaled to the maximum change for each ES for better readability). A negative value indicates a loss of ES, while positive values indicate an increase in ES.

decrease the risk of disturbances in the long term (Seidl et al., 2018). In addition, retaining dead wood can help maintain some ES after disturbances, but may increase the risk of subsequent bark beetle infestations (Seidl and Rammer, 2017; Stadelmann et al., 2014).

To take these long-term processes into account, a useful approach may be to couple the ES models with dynamic vegetation models at the landscape scale (Seidl et al., 2014a; Temperli et al., 2020). Such process-based models would also allow to consider climate effects in more depth, but contain also considerable uncertainties (Petter et al., 2020), which could be integrated in the BN-approach by running multiple simulations with varying parameters. At the same time, the ES models can also be used to identify important variables that should be modelled over time. For example, although dynamics of dead wood are usually not explicitly modelled in dynamic vegetation models (Petter et al., 2020), our results indicate that dead wood plays an important role in forest ES. A combination of ES models and dynamic vegetation models could improve predictions of future ecosystem services, and allow us to address the long-term adaptive capacity of forests, which is an important aspect of forest vulnerability (Lecina-Diaz et al., 2021).

4.2. Bundles of ES risk and implications for management

By mapping not only the value of ES, but also the associated risks, additional valuable information can be added to traditional ES-bundle analyses. Our results show a correlation between the expected value and risk to ES for carbon sequestration and avalanche protection, indicating a trade-off between the level and stability of ES provision. This type of trade-off has also been identified in simulation-based studies of forest ES dynamics (Albrich et al., 2018; Temperli et al., 2020). However, this relationship is not homogeneous in space, and less pronounced for other ES. Mapping the risks to ES is therefore important information for forest managers under a changing disturbance regime, who face decisions about where to control and where to embrace the effects of natural disturbances (Kulakowski et al., 2017; Seidl et al., 2018). In this study, we mapped the ES and risk to ES at a 100 m resolution, which allows us to identify patterns at the landscape scale while limiting the computational time needed to run the models, and which corresponds to the grid size of available validation data. To identify patterns related to fine-scale differences in forest structure and inform forest management at the local scale, the same models could be applied at a higher resolution (as high as 10 m, corresponding to the resolution of the classification based on Sentinel-2 images). Higher resolution data would be particularly useful to refine the habitat suitability models for individual species, which could be improved with additional forest-structural variables (Zellweger et al., 2013).

Based on the cluster analysis of ES risks, we can identify not only priority areas with a high risk of losing ES (e.g. cluster 1, Fig. 5) but also areas with a more stable provision of several ES (clusters 5 and 6). While a high risk of losing ES indicates areas where interventions may be needed to ensure the demanded level of ES provision, areas of stable provision are important in terms of the insurance value of ecosystems (Baumgärtner and Strunz, 2014). Ecosystem management based on risk to ES may therefore differ from management based on the current value of ES.

4.3. Protected and non-protected areas

Our results indicate a strong effect of strict protection on ES and risks to ES. Overall, we find a lower level of risk in the strictly protected Swiss National Park compared to both the surroundings of the park (Lower Engadin and Val Müstair), and the more densely used area of Davos. While the forests of Davos provide a wider range of ES, the provision of these services is at risk in some parts of this study area under an intensifying disturbance regime. Forest managers are therefore faced with high uncertainty regarding issues such as the long-term effectiveness of disturbed forests for natural hazard protection and their perception by visitors. In contrast, the lack of human intervention in the SNP results in a higher quality of habitats and a potential increase of ES under the disturbance scenario. It is important to note that we only modelled the habitats of three species and weighted all the species equally. Although the capercaillie and three-toed woodpecker are considered to be indicator species for species-rich forests (Roberge and Angelstam, 2006; Suter et al., 2002), other species may be negatively affected by natural disturbances (Thom and Seidl, 2016), and a different prioritization of species might affect the modelling results.

The differences between protected and non-protected areas are driven by regulations (e.g. lack of salvage logging and limited recreation outside of hiking trails), but also by differences in demand for ES, such as the smaller amount of infrastructure at risk of avalanches inside the park, and different visitor preferences. Therefore, the differences are more pronounced for services with a local demand (e.g. avalanche protection) than for services with a global demand (e.g. carbon sequestration).

In many protected areas, the concept of ES is not explicitly addressed in management plans (Palomo et al., 2014). In the case of the Swiss National Park, the park managers have a federal mandate to let natural processes take their course, enable research in an undisturbed ecosystem, and to educate visitors (Haller, 2014). In contrast to many other protected areas worldwide that aim to foster both conservation and sustainable development (Dudley, 2008), these clear management objectives limit the need for decisions about trade-offs between ES in the SNP. Nonetheless, assessments of ES can help demonstrate the importance of such protected areas (Kettunen et al., 2008), such as the insurance value of ecosystems in the park, where the risk to ES is low compared to non-protected areas. In addition, information about ES dynamics and risk in the absence of human intervention can provide valuable information for managers of non-protected areas (Hanna et al., 2020).

5. Conclusions

In this study, we assessed the spatially heterogeneous risk to mountain forest ES posed by natural disturbances. By mapping bundles of risk to ES, we can identify areas with high ES value and a high risk of losing ES, as well as areas with a stable provision of ES, and this type of information can serve as a basis for risk-based decisions about ecosystem management. Although many uncertainties remain about mountain forest dynamics under a changing climate, our results show that retaining dead wood in the stand can help mitigate the effects of natural disturbances on forest ES. When comparing mountain forests in the non-protected area of Davos with those in the strictly protected Swiss National Park, our findings indicate a lower risk to ES in the protected area. These differences are largely driven by differences in demand for ES, highlighting the need to include demand in assessments of risk to ES.

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.

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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.2021.113188.

Credit author statement

Ana Stritih: Conceptualization, Formal analysis, Writing – original draft; Peter Bebi: Conceptualization, Writing – review & editing; Christian Rossi: Writing – review & editing; Adrienne Grêt-Regamey: Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

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