



# The impact of land-use legacies and recent management on natural disturbance susceptibility in mountain forests

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## ABSTRACT

Mountain forests provide a wide range of ecosystem services, including carbon sequestration and protection from natural hazards. Forest cover in the European Alps has increased over the last century, but in recent years, these forests have experienced an increasing rate of natural disturbances by agents such as windthrow, bark beetle outbreaks, and forest fires. These disturbances pose a challenge for forest management, making it important to understand how site and stand characteristics, land use legacies and recent management influence disturbance probability. We combined a dataset of forest disturbances detected from space with in-situ forest management records, allowing us to differentiate between different types of disturbances for the Canton of Graubünden, Switzerland, in the years 2005–2018. The resulting dataset of over 28'000 attributed disturbance patches (corresponding to a disturbed forest area of ca. 23'600 ha) was combined with information on topography, forest structure, and historical forest cover. A machine-learning approach was used to investigate the non-linear and interacting relationships between potential drivers and disturbance occurrence. Natural disturbances (especially windthrow and bark beetle outbreaks) were most common at lower elevations, on shallow and south-facing slopes, and in even-aged, spruce-dominated stands with a closed canopy. Forests established in the 20th century were significantly more susceptible to natural disturbances than forests that were already present before 1880, which may be due to the uniform age and vertical structure of secondary forests, as well as legacy effects of former agricultural use. On the other hand, forest management more often took place in forests present before 1880. Management interventions (such as thinning) in turn increased the susceptibility to natural disturbances in the short term. This finding emphasizes the need to balance short-term increases in disturbance susceptibility with long-term benefits in forest resilience when planning management interventions in mountain forests. Our findings highlight the importance of considering multiple interactive drivers, including management and land-use history, for understanding forest disturbance regimes.

## 1. Introduction

Forests provide important ecosystem services, such as regulating the global carbon cycle, supplying renewable resources, and providing habitat to a wide variety of species. In mountain regions, forests provide protection from natural hazards, such as avalanches, shallow landslides, and rockfall, which is essential to mountain communities (Moos et al., 2018). In the European Alps, forest cover has increased during the last century (Bebi et al., 2017; Loran et al., 2016; Mietkiewicz et al., 2017), which contributed to an increase in forest carbon stocks (Bolliger et al., 2008) and natural hazard protection (Sebald et al., 2019). However, past

land use has legacy effects on forest structure (Bebi et al., 2017), tree species composition (Chazdon, 2008; Thom et al., 2019), and soil characteristics (Brudvig et al., 2013), all of which may influence forests' susceptibility to natural disturbances (Munteanu et al., 2015; Seidl et al., 2011b) and their capacity to provide ecosystem services (Chazdon, 2008; Sutherland et al., 2016; Thom et al., 2019). For instance, forest expansion creates a more homogeneous landscape (Kulakowski et al., 2011; Mietkiewicz et al., 2017), which can facilitate insect outbreaks (Raffa et al., 2008) and increase the risk of natural disturbances (Turner et al., 2013). Hence, there is a need to consider the legacies of past land use when quantifying the susceptibility of forests to increasing

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disturbances.

Forest canopy mortality has increased in Europe over the last 40 years (Senf et al., 2020; 2018). The Alps have seen a growing rate of bark beetle outbreaks and large-scale windthrow events (Seidl et al., 2014b; Usbeck et al., 2010). Increasing disturbance rates may jeopardize not only the forests' role as carbon sinks (Pugh et al., 2019; Seidl et al., 2014b; Yu et al., 2019), but also their capacity to provide protection from natural hazards (Sebald et al., 2019; Vacchiano et al., 2016). Forest disturbances also affect the aesthetics of the landscape (Sheppard and Picard, 2006), its value for recreation (Flint et al., 2012), and biodiversity (Thom and Seidl, 2016). Lastly, disturbances increase the variability of the supply of renewable biomass and pose a challenge for long-term planning in forest management (Albrich et al., 2018). Natural disturbances have therefore become a key concern for forest managers (Kulakowski et al., 2017; Nikinmaa et al., 2020). Understanding the spatial and temporal dynamics of disturbances and the factors that affect a forests' susceptibility to disturbance can help define priorities for intervention (Seidl et al., 2018) and integrate risk into forest management decisions (Hanewinkel et al., 2011). However, our understanding of disturbances is still incomplete, especially in landscapes with strong management legacies, such as many mountain forests in Europe.

The climatic, topographic and stand factors that drive the occurrence of disturbances and forest susceptibility have been studied extensively (Hanewinkel et al., 2011; Seidl et al., 2011a). The occurrence of forest disturbances is mainly driven by climatic drivers, such as storm winds (Krejci et al., 2018; Seidl et al., 2011b; Wohlgemuth et al., 2008), heavy snowfall (Hlásny et al., 2011), or drought and high temperatures that facilitate bark beetle development (Faccoli, 2009; Stadelmann et al., 2013) and forest fires (Conedera et al., 2011; Pezzatti et al., 2010). When analysing spatial patterns of disturbances, climatic factors can be exacerbated by topography. For example, bark beetle outbreaks are more frequent on drier, south-exposed slopes (Stadelmann et al., 2014), while a complex topography can constrain disturbance size (Senf and Seidl, 2018). Forest susceptibility to disturbance also depends on stand characteristics, such as species composition, particularly the proportion of bark beetle host trees (e.g., Norway spruce, *Picea abies* (L.) Karst.) (e.g. Krejci et al., 2018; Netherer and Nopp-Mayr, 2005; Temperli et al., 2013), stand age, tree height, density, and growing stock (Díaz-Yáñez et al., 2017; Radl et al., 2017; Seidl et al., 2011b; Stadelmann et al., 2013).

Empirical research on spatial drivers of disturbances in managed forests is often limited to individual disturbance events or short time periods (Seidl et al., 2011a). Dendrochronological research of long-term disturbance dynamics, in turn, has mostly focused on primary (unmanaged) forests (Čada et al., 2020; Janda et al., 2017; Panayotov et al., 2015). Research relating disturbance dynamics to past and present management thus mostly relies on process-based simulations (Seidl et al., 2018; Temperli et al., 2017; 2013; Thom et al., 2018), which have found that both the legacies of past land use (Thom et al., 2018) and current management strategies have a strong effect on forest disturbance dynamics (Seidl et al., 2018). Information on historical land use and management is, however, rarely available for empirical studies of disturbance dynamics. A study in the Carpathian mountains found a higher disturbance rate in forests established after 1860 compared to "old" forests (Munteanu et al., 2015). These "new" forests may be more susceptible to natural disturbances due to their homogeneous species composition and uniform age structure (Munteanu et al., 2015; Seidl et al., 2011b), as a high disturbance rate in recent years has also been observed in primary and unmanaged spruce stands that developed after major disturbances 19th century (Čada et al., 2016; Janda et al., 2017; Panayotov et al., 2015). However, a higher disturbance rate in "new" forests could also be the result of different management strategies (e.g., clear cuts of plantations after a 70–120-year rotation). Since Munteanu et al. did not differentiate between anthropogenic and natural disturbances, or control for the influence of forest structure, these effects remain unresolved.

In this study, we aim at improving our understanding of mountain forests' susceptibility to natural disturbances, particularly how susceptibility is influenced by management and land-use legacies. To this end, we combined remotely-sensed disturbance data with in-situ forest management information to derive a large dataset of forest disturbances for the Canton of Graubünden in Switzerland (covering a forest area of 210'000 ha) for the years 2005–2018. This dataset was combined with historical maps of forest cover and land use, and a machine-learning approach was used to quantify the non-linear and interacting effects of (i) site and stand characteristics, (ii) historical land use, and (iii) recent forest management on the susceptibility of forests to both natural and anthropogenic disturbances. We hypothesized that while stand and site characteristics are important drivers of natural disturbance risk, susceptibility to both natural and anthropogenic disturbances would be strongly influenced by past land use and management.

## 2. Methods

### 2.1. Study area

Graubünden is the largest Canton of Switzerland, covering 7'105 km<sup>2</sup> in the southeast of the country. It is a mountainous region that includes the upper Rhine and Inn catchments, with elevations ranging from 260 to 4049 m a.s.l. and a mostly inner-alpine climate. Traditionally, the landscape has been shaped by mountain agriculture, but many former pastures have been abandoned during the 20th century. Land abandonment and afforestation have contributed to an increase in forest cover (Loran et al., 2016) of over 30% between 1880 and 2000 (Ginzler et al., 2011). Today, almost 30% of the canton is forested (Abegg et al., 2020). Most of the forests in Graubünden are conifer-dominated, with spruce as the most common species. At high elevations, spruce gives way to larch (*Larix decidua* L.) and pines (*Pinus cembra* L., *Pinus mugo* Turra), while at lower elevations, Scots pine (*Pinus sylvestris* L.) is dominant on some of the driest sites. European beech (*Fagus sylvatica* L.) and other broadleaved species as well as silver fir (*Abies alba* Mill.) occur to a limited extent in valleys with a less continental climate. The upper treeline is at around 1800 m a.s.l. in the northern part of the Canton and almost 2400 m a.s.l. in the inner-alpine Engadin valley. Around 60% of the forests in Graubünden are protective forests, which protect people and infrastructure from natural hazards such as avalanches, rockfall, and shallow landslides (Kanton Graubünden, 2018). Forest management mostly takes place in the form of small-scale interventions, many of which are aimed at maintaining the forests' resilience and protection capacity (Temperli et al., 2017). Common natural disturbances in the region include windthrow, such as the storm Vaia in 2018 (Kanton Graubünden, 2018), snow breakage, and bark beetle outbreaks (Bebi et al., 2017). Snow avalanches also play an important role in forest dynamics (Kulakowski et al., 2011), while forest fires are less frequent but of increasing importance (Pezzatti et al., 2016).

### 2.2. Disturbance dataset

The analysis was based on a spatially explicit dataset of forest disturbances derived from Landsat time series (Senf and Seidl, 2020). The map gives information about the year of the most severe disturbance per pixel at 30 m resolution over the period 1986–2018 (the product is openly available for forests across Europe for the years 1986–2016 at <http://doi.org/10.5281/zenodo.3924381>). In case of multiple disturbances at the same location, only the most severe disturbance is detected. The remote sensing product currently does not contain information about the disturbance agent (e.g. windthrow or bark beetle outbreak), nor does it differentiate between natural and anthropogenic disturbances. We therefore combined the Landsat-based data with forest management information from the Cantonal Office for Forest and Natural Hazards (AWN, 2019a; 2019b). Available as a spatially explicit database from 2005 onwards, it contains information about forest

management interventions, including sanitary cuts after natural disturbances and planned interventions for wood harvesting and protection forest management.

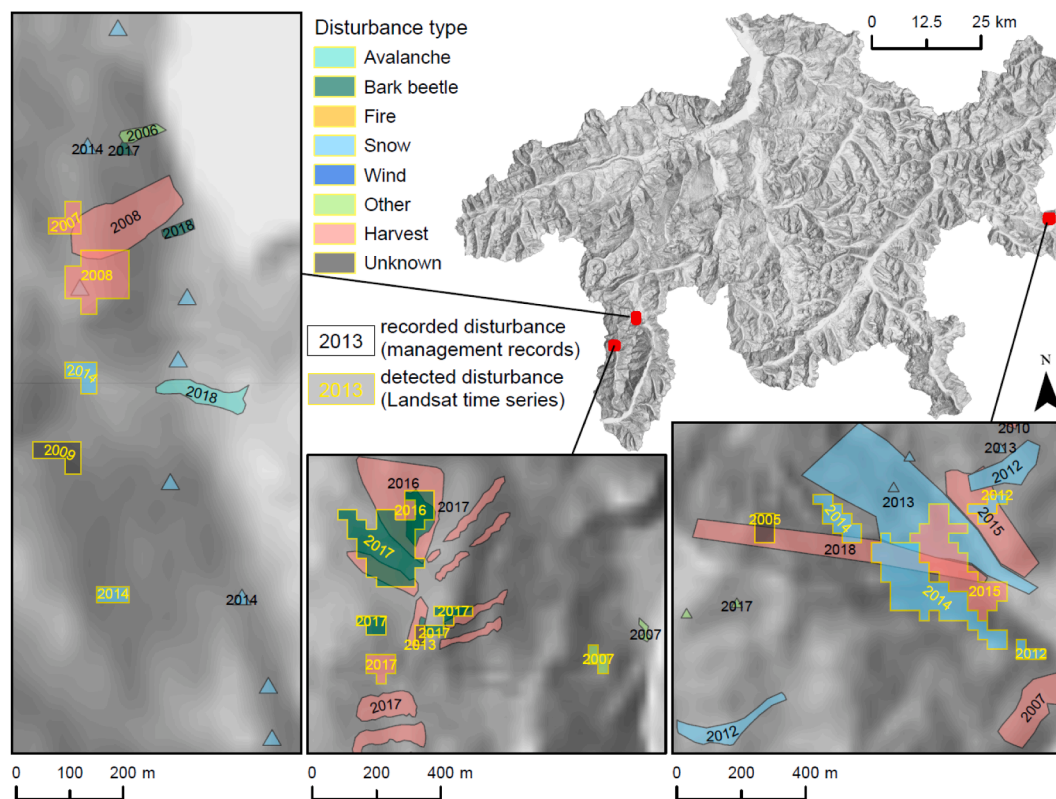
The raster of satellite-detected disturbances was converted into polygons, where spatially continuous disturbances from the same year were considered as a distinct disturbance patch, and overlaid with management records (see Fig. 1). A satellite-detected disturbance was assigned to a recorded event when it occurred within a distance of up to 200 m (to account for mapping inaccuracies, with priority given to closer events) and  $\pm 1$  year of the recorded event (since some disturbances and management interventions are only recorded the following year). In addition, we used the swissfire database (Pezzatti et al., 2010) and the StorME record of natural hazard events (FOEN, 2019) to attribute disturbances to fire or avalanches, respectively. In ambiguous cases, that is where a disturbance event detected from satellite data overlapped with multiple recorded disturbances, the most likely disturbance agent was determined manually based on the size and shape of the disturbed area and the event descriptions in the management records. When a natural disturbance was followed by salvage logging, the disturbance event was assigned to the original cause of the disturbance. A disturbance cause could be assigned to 75% of the disturbances detected in the satellite time series, whereas 25% correspond either to unreported natural disturbances or false positives (see Table 2). This resulted in a spatially explicit dataset of forest disturbances attributed to individual disturbance agents, distinguishing avalanches, bark beetles, forest fires, snow breakage, windthrow, other natural disturbances, and anthropogenic disturbances for the whole Canton Graubünden for the years 2005–2018. Anthropogenic disturbances include harvesting and other silvicultural interventions not caused by natural disturbances.

### 2.3. Modelling

In order to model the spatial factors that affect disturbance risk, we compared the 28'002 disturbed areas ("presence") with 30'000 randomly sampled non-disturbed forest locations ("absences" with an area of 0.28 ha, corresponding to the median patch size of natural disturbances, see Table 2) across the whole study area. Then, a random forest classifier (Breiman, 2001) was used to classify disturbed vs. non-disturbed locations based on spatial predictors (see Table 1).

The predictors were selected based on disturbance drivers commonly reported in the literature, and included topographic site descriptors (calculated from a DEM, swisstopo) and in-situ forest structural variables from a stand map (canopy cover, species composition, vertical structure, see Table 1). In addition, two digitalized historical maps were used to investigate the effect of land-use history. The so-called Siegfried maps were a series of topographic maps drawn at the 1:25'000 scale in most of Switzerland and 1:50'000 in the Alps, where the first map was created in the years 1872–1908, and the last in 1917–1944 (Loran et al., 2016). Based on forest cover information from these maps, we differentiated between three classes of land-use history: (i) forests that were present before the first Siegfried map (ca. 1880), (ii) forests established in the time between both historical maps (ca. 1880–1920) and (iii) forests established after the last Siegfried map (ca. 1920). Furthermore, spatially explicit data about tree heights was available in the form of a canopy height model from 2015. In order to make use of this predictor, we focused the main part of our analysis on disturbances that occurred between 2016 and 2018 (3'668 disturbance patches). As an additional predictor, we included a variable describing whether a management intervention (including thinning, harvesting, salvage logging, and measures to promote regeneration) occurred during the previous 11 years (2005–2015).

A random forest model was fitted for natural and anthropogenic



**Fig. 1.** A hillshade map of the Canton of Graubünden (swisstopo) with close-ups showing both satellite-detected disturbances (yellow labels) and management records (black labels). Triangles indicate approximate locations of natural disturbance damages from the forest management records. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 1**

Description of the predictors used in the analysis of disturbance risk, with the values found in the case study area. The mean (and standard deviation) are shown for continuous variables, while the frequency of categories is shown for factor variables. Variables shown in bold were selected for the final models.

Predictor variable	Description	Values	Data source
<b>Elevation</b>	Digital elevation model (25 m-resolution)	1447 (363) m a.s.l.	DHM25 (swisstopo, 2004)
<b>Slope</b>	Slope angle	29 (10) °	
<b>Aspect</b>	4 classes: North, East, South, West.	North 28%, East 23%, South 21%, West 27%	
<b>Topographic exposure</b>	Calculated as the difference in elevation to mean of a focal window (5 × 5 cells of 25 m-resolution), ranging from negative values (concave) to positive (convex).	0.2 (5) m	Guisan et al., 2017; Stadelmann et al., 2014
<b>Cover</b>	Canopy cover (0–100%)	70 (14) %	AWN, 2019b
<b>Spruce</b>	Share of Norway spruce in the stand, from 0 (none) to 100 (pure spruce stand).	62 (35) %	
Broadleaves	Share of broadleaves in the stand.	9 (22) %	
Dominant species	Categorical variable indicating the dominant tree species.	Broadleaf: 5% Spruce: 52% Other conifer: 37% Mixed: 7%	
<b>Structure</b>	2 classes: even-aged and uneven-aged as categorized by experts from the Cantonal Office for Forest and Natural Hazards.	Even: 60% Uneven: 40%	
Species composition	Share of deciduous trees in the canopy cover, derived from remote sensing	18 (25) %	Swiss NFI (Waser et al., 2017)
<b>Land-use history</b>	3 classes: Pre-1880: present before 1872–1908 Post-1880: established after 1872–1908 and before 1917–1944 Post-1920: established after 1917–1944	Pre-1880: 63% Post-1880: 10% Post-1920: 27%,	Siegfried maps (1872–1908 and 1917–1944), (Loran et al., 2016)
<b>Canopy height</b>	Mean canopy height in 2015, derived from a stereo-imaging digital surface model at a 1 m resolution.	16 (5) m	Ginzler and Hobi, 2015
Height variability	Standard deviation of the 2015 canopy height model.	5 (3) m	
<b>Management</b>	Binary variable indicating whether there was a recent management intervention in the years 2005–2015.	Yes: 21% No: 79%	AWN, 2019a

disturbances separately, as well as for each individual type of natural disturbance, both for the period 2016–2018 and for the whole period (2005–2018, without the predictors canopy height and management). Random forest is a machine learning algorithm where the classification is based on an ensemble of decision trees (Breiman, 2001). The imbalanced distribution of classes (i.e. many more absences than presences) may introduce a bias towards the more represented absences in the classifier, which aims to minimize the overall error rate (Chen et al., 2004). To deal with this, an equal number of data points was sampled from both classes for each classification tree in the random forest.

Two indicators were used to quantify the importance of variables in the random forest models. The “Mean Decrease Gini” expresses the total decrease in node impurities (measured with the Gini index) when a variable is used for splitting, averaged over all classification trees (Breiman, 2001). Since the “Mean Decrease Gini” can be biased towards variables with a wide range or higher number of classes (Strobl et al., 2007), we also calculated a permutation-based variable importance, which measures how much the accuracy of the model is decreased by permutations in each predictor (Genuer et al., 2015). Among correlated predictors (Pearson correlation > 0.4), such as different descriptors of species composition (see Table 1), only the variable with the highest importance was used in the final model. The effects of the predictor variables and interactions between them were further explored using partial dependence plots, where predicted probabilities are calculated for each value of a predictor variable (or each combination of multiple variables), while varying all the other variables in the model (Friedman, 2001; Greenwell, 2018). The individual partial dependence plots thus depict the marginal effect of each variable, which can help identify non-linear effects, while partial dependence plots with multiple variables can illustrate interactions between variables. In order to be able to compare the effects of predictors among different types of disturbances, the same combination of predictors was used for all disturbance agents.

To evaluate the models’ quality, we performed a tenfold split calibration–validation of each model, where a subset of 80% of the data was used for training and 20% for validation, and calculated the corresponding area under the receiver operating curve (ROC). The ROC is generated by plotting a model’s true positive against its false positive

rate at different thresholds of the probability of presence. The area under the curve (AUC) is thus an indicator of model performance that measures how well a model can distinguish between presences and absences, independent of the probability threshold used for assigning a data point as present (Hosmer and Lemeshow, 2000).

To verify the robustness of the variable effects found in the random forest models, we also fitted a binomial generalized linear model (Venables and Ripley, 2002) and a gradient boosting machine classifier (Friedman, 2001; Greenwell et al., 2019) for each disturbance type with the same predictor variables, calculated the corresponding AUC and analysed the variable importance of each model. The gradient boosting approach is similar to the random forest, but the trees are built sequentially, where each new tree aims to minimize the errors of the previous trees (Friedman, 2001; Greenwell et al., 2019). The variable importance in the gradient boosting machine is expressed as the relative contribution of each variable to the overall performance of the classifier. The binomial generalized linear model is a logistic regression, where the degree of association between each variable and the response is expressed through the estimated coefficients. All the analyses were carried out in R (R Core Team, 2019).

### 3. Results

The combination of the Landsat-based disturbance map with the management records as well as the fire and natural hazard databases resulted in the identification of 28’002 individual disturbance patches for the years 2005–2018 (see Fig. 2), with a mean disturbance patch size of 0.85 ha and an average of 1’647 ha of disturbed area per year.

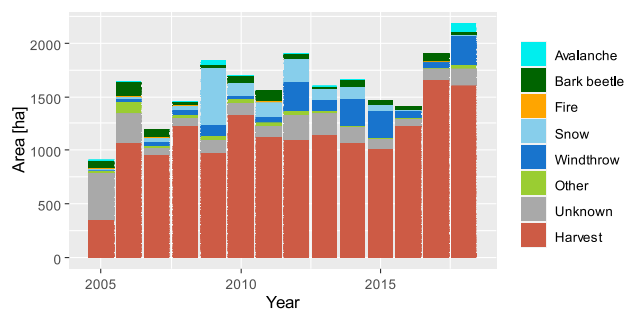
Overall, 58% of forest management records (including sanitary cuts due to natural disturbances and anthropogenic interventions) were detected as disturbances in the Landsat-based disturbance map. Among all disturbances in the Landsat-based disturbance map, 25% could not be assigned to any disturbance recorded in the management data, the natural hazard or the forest fire database. This suggests a commission error of approximately 25% in the Landsat product, although some of these events may be natural disturbances that were not recorded in the forest management dataset.



**Table 2**

Overview of the number of disturbances and their patch size per type for years 2005 – 2018. The dataset includes disturbances detected from Landsat timeseries, forest management records, StorME and swissfire datasets in the Canton of Graubünden. The column “undetected” indicates the percentage of recorded disturbances (natural and management-related) that were not detected in the remote sensing product, while the row “unknown” shows the disturbances detected in the time series that were not recorded in the management data.

Type	Number	Patch size [ha]					Undetected
		mean	sd	median	5th percentile	95th percentile	
Harvest	16'226	1.03	1.89	0.45	0.08	3.96	43%
Avalanche	163	1.25	3.71	0.45	0.09	3.50	19%
Bark beetle	1'628	0.49	1.15	0.19	0.05	1.89	54%
Fire	86	0.86	1.44	0.36	0.09	3.33	7%
Snow	1'647	0.85	4.00	0.27	0.05	2.70	34%
Windthrow	2'232	0.77	2.10	0.27	0.05	2.88	42%
Other	446	0.88	2.03	0.36	0.05	4.10	34%
Unknown	5'574	0.40	0.48	0.27	0.09	1.08	–



**Fig. 2.** Time series of disturbances in the Canton of Graubünden between the years 2005 and 2018. The dataset includes disturbances detected from Landsat timeseries and forest management records in the Canton of Graubünden, where the disturbance agent is assigned based on forest management records as well as information on natural hazards (StorME) and forest fires (swissfire).

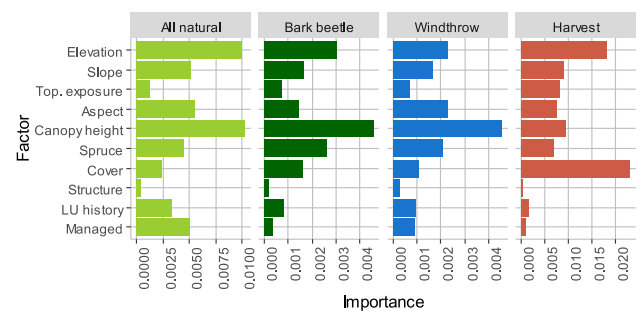
The random forest models of different disturbance types reached AUC values of around 0.8 for the years 2016–2018 (see Table 3), which indicates good model performance (Hosmer and Lemeshow, 2000). The exception are disturbances with very few observations, such as forest fires and snow breakage events. The directionality of effects, that is whether disturbance susceptibility increases or decreases with a predictor variable, was consistent when running the random forest model for the years 2005–2018, as well as with the gradient boosting and generalized linear models (see Appendix for all model performances and variable importance). The effects reported herein are thus robust to variation in the input data, as well as variations in the modelling approach.

The strongest predictors of natural disturbance susceptibility are canopy height and topographic factors (Fig. 3). All of the modelled disturbance agents are more likely to occur at lower elevations (except avalanches) and on south- and east-facing slopes (Fig. 4). Susceptibility decreases sharply on steep slopes above ca. 35° (except for avalanches

**Table 3**

Performance of the random forest models (AUC – area under the receiver operating curve) across different types of disturbances for the period 2016–2018. N indicates the number of disturbance events, where 80% were used to calibrate and 20% to validate the models in a tenfold split calibration-validation procedure.

Disturbance	n	AUC
All natural	1164	0.79
Avalanche	20	0.82
Bark beetle	358	0.81
Fire	11	0.76
Snow	41	0.75
Windthrow	397	0.83
Harvest	2504	0.80

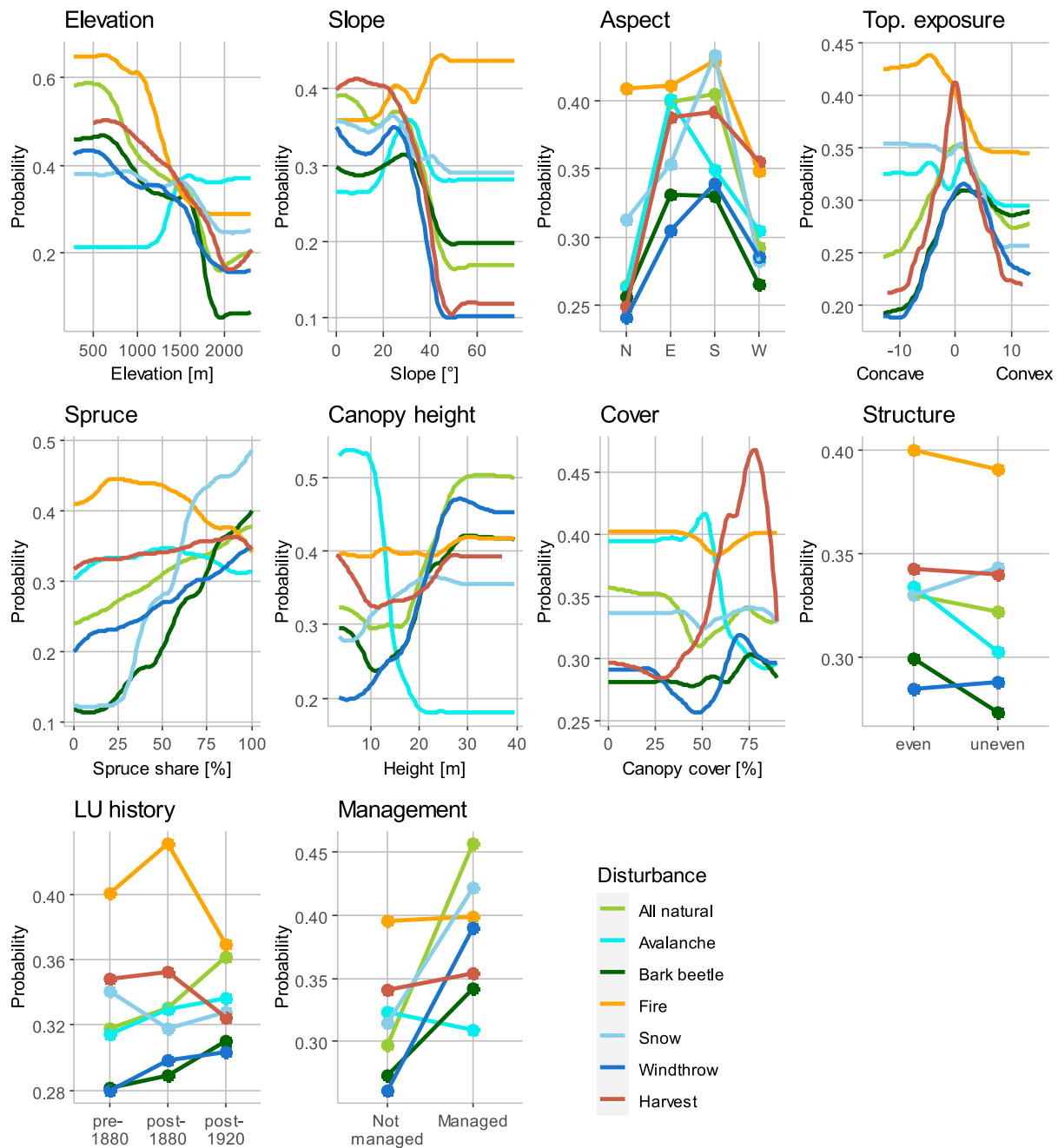


**Fig. 3.** Permutation-based variable importance in the random forest models for all natural disturbances, bark beetle, windthrow, and harvest (the most common types of disturbances in the region) in the years 2016–2018. The absolute values of the importance measure are not comparable due to the different sample sizes in each model. Other indicators of variable importance are shown in the Appendix (Figure A1 and Table A2). For variable definitions, we refer to Table 1.

and forest fires). Topographic exposure has a strong non-linear effect on disturbance risk, where sites with a neutral exposure (i.e., neither convex nor concave topography) are most susceptible. Spruce-dominated stands show a higher susceptibility to natural disturbance than mixed stands, particularly in the case of bark beetle outbreaks. Taller canopies also correspond to a higher risk of disturbance for all disturbance agents (except avalanches). This effect is particularly strong for windthrow, but levels off at canopy heights > 25 m (see Fig. 4). Bark beetle outbreaks are more common in even-aged stands, whereas uneven-aged (i.e. layered) stands are more exposed to windthrow. Overall, however, the effect of vertical structure on susceptibility is weak compared to other stand characteristics.

We found a strong interaction between species composition and canopy cover. In stands with a high proportion of spruce, a higher canopy cover results in a higher natural disturbance susceptibility, whereas in stands of other species, susceptibility decreases with canopy cover (see Fig. 5). The high natural disturbance susceptibility of closed-canopy spruce stands is particularly pronounced in forests established after ca. 1920. These stands are more susceptible to natural disturbances than forests established earlier even when controlling for stand and site characteristics (Fig. 4). Although the importance of land-use history in predicting disturbance susceptibility is low compared to topographic factors and species composition, its effect is consistent across different types of natural disturbances (windthrow, bark beetle, and avalanches, as well as snow breakage and fire when analysing the whole time period 2005–2018, see Appendix, Figure A2), and across different topographic conditions. In stands established between 1880 and 1920, the disturbance susceptibility was lower than in stands established after 1920, and was lowest in areas that were forested before 1880.

In contrast to natural disturbances, anthropogenic disturbance



**Fig. 4.** Smoothed partial dependence plots of the random forest model of disturbance probability for different disturbance agents for the years 2016–2018. The x-axis shows the values of the predictor and the y-axis indicates relative disturbance probabilities. Note that the scale of the axis differs between plots to better visualize the effects of individual predictors. Partial dependence plots for all disturbance agents and the whole time period (2005–2018) are shown in the Appendix, Figure A2).

(harvesting) is more common in forests that were established before 1920, particularly in dense stands, whereas canopy height, vertical structure and fraction of spruce have a smaller effect. In terms of topography, harvesting follows a similar spatial pattern to natural disturbance, and occurs more often at lower elevations and south- and east-facing slopes below 40°. Canopy cover is a more important predictor of anthropogenic than of natural disturbances, where forests with a cover of around 75% are most likely to be harvested.

When analysing disturbances that occurred between 2016 and 2018, we found that forests that had been managed (e.g., thinned) during the previous eleven years were more likely to experience another disturbance than forests that remained untreated in the previous period (see

Fig. 6). The relationship between recent management and disturbance susceptibility was particularly strong for windthrow and less pronounced for anthropogenic disturbances (Fig. 4).

## 4. Discussion

### 4.1. Spatial predictors of disturbance susceptibility

Our results reaffirm the important role of topography, which effects a site’s microclimate, in determining the susceptibility to forest disturbances (Hanewinkel et al., 2011; Stadelmann et al., 2014). Forests at lower elevations, on shallow, south- and east- facing slopes are more at

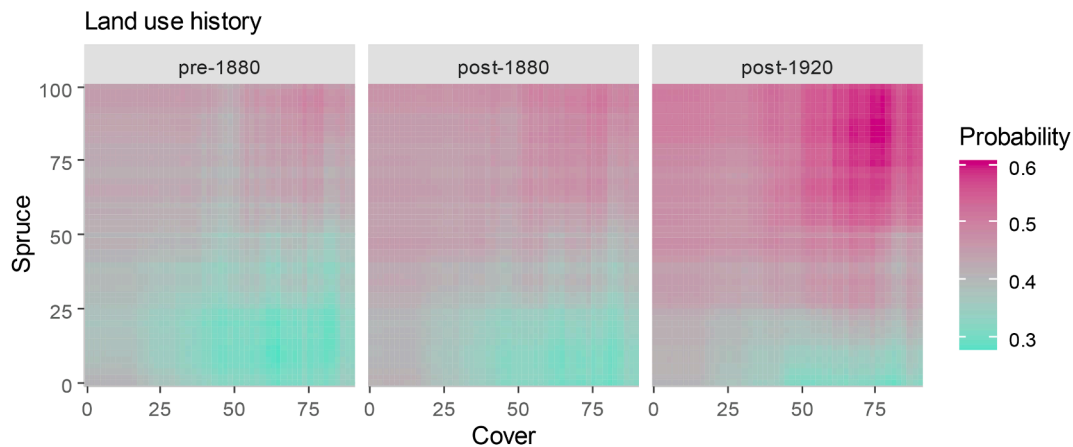


Fig. 5. Interaction between canopy cover, spruce share, and land-use history class in the random forest model of relative natural disturbance probability between 2005 and 2018.

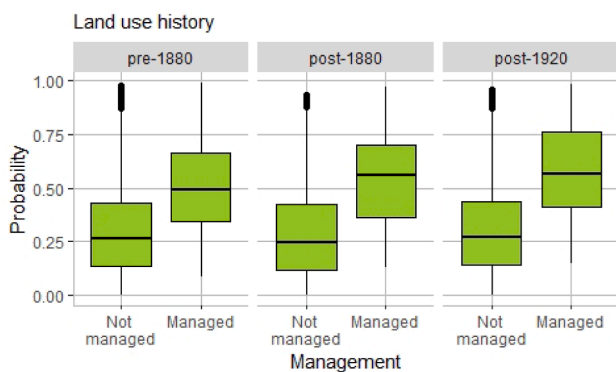


Fig. 6. Comparison of natural disturbance probability in managed and unmanaged stands per land-use history class, based on predicted values of the random forest for all natural disturbances between 2016 and 2018, where the hinges of the boxplot correspond to the 25th and 75th percentiles of predicted probabilities over all presence and absence points used in the analysis.

risk of windthrow, snow breakage, and bark beetle outbreaks. While it is well known that warmer and drier sites are more suitable for the development of bark beetles (Netherer et al., 2015; Netherer and Nopp-Mayr, 2005) and the occurrence of forest fires (Conedera et al., 2011), the consistent patterns across different disturbance agents indicate that warmer and drier conditions also make forests more susceptible to other types of natural disturbances. These conditions are especially critical for Norway spruce, which has a low tolerance to drought (Vitali et al., 2017), and are likely to be further exacerbated by future climate warming (McDowell et al., 2020; Seidl et al., 2014b). Anthropogenic disturbances (harvesting and other silvicultural interventions) are also more likely at lower elevations and on gentle slopes, which reflects the better accessibility of these sites.

Among stand characteristics, canopy height is the most important predictor of natural disturbance susceptibility. This is unsurprising, as taller trees are more likely to experience damage from windthrow and snow breakage (Díaz-Yáñez et al., 2017; Seidl et al., 2014a). Trees are likely to reach large heights in dense stands, where competition for light is strong. A higher canopy cover thus contributes to higher disturbance susceptibility (Netherer and Nopp-Mayr, 2005; Radl et al., 2017). Our findings confirm this effect for spruce-dominated forests, but not in stands with a heterogeneous species composition (Fig. 5).

#### 4.2. Land-use legacies

Our results show that secondary forests (established during the 20th

century) are more susceptible to natural disturbances than forests that were already present during the 19th century. While most of the management in post-1920 stands is related to sanitary cuts as a response to natural disturbances (Fig. 4), stands established before 1920 are more likely to be actively managed (Bebi et al., 2017). The more frequent harvesting in pre-1880 stands with a high canopy cover (Fig. 4) may reflect the prevailing forest management strategy, which prioritizes the initiation of regeneration in dense forests (AWN, 2018).

We note that the land-use history class does not necessarily correspond to stand age, as forests established prior to 1880 may have a more heterogeneous age structure than secondary forests established after 1920, which were often initiated in one uniform age cohort. Bebi et al. (2017) analysed the difference in structure between pre- and post-1880 forests in NFI plots across Switzerland, and found that “new” forests do not only have a lower total growing stock, but are also vertically more homogeneous. In unmanaged mountain spruce forests in Central and Eastern Europe, uniform stands established after large disturbance events in the mid-19th century are now experiencing a new pulse in disturbances (Čada et al., 2016; Janda et al., 2017; Panayotov et al., 2015). In our study, homogeneous spruce stands established only 80–100 years ago are most susceptible to disturbances. These stands have often already experienced considerable self-thinning, with severe competition, high levels of stress and high mortality (Krumm et al., 2012). Small gaps due to self-thinning can make these dense stands with short crowns and high height-diameter ratios even more susceptible to disturbance (Panayotov et al., 2016; 2015).

Besides the uniform age structure of forests established during the 20th century, disturbance susceptibility may be influenced by other effects of land-use legacy. For similar stand characteristics, our results indicate that forests established on former agricultural land after 1920 are more susceptible to natural disturbances than forests that were already present at the end of the 19th century (see Fig. 5). Post-agricultural forest soils have been found to have a lower soil water capacity, lower nitrogen and soil organic matter, and higher phosphorus content than old forest soils (Brudvig et al., 2013). In addition, the presence of pathogenic fungi may be higher in spruce plantations (Holuša et al., 2018). All of these factors may exacerbate forests' vulnerability to drought and make them more susceptible to other natural disturbances. Although the large-scale historical forest cover data used in this study does not contain information on historical management practices, differentiating between afforestation and forest encroachment on former agricultural lands would help to disentangle the more specific legacy effects.

The higher susceptibility of forests established during the 20th century to natural disturbances is particularly relevant as secondary forests are increasing worldwide through forest expansion and afforestation,

while old forests are being lost due to land use change, harvest and disturbances in many parts of the world (McDowell et al., 2020). Old forests are better at providing a wide range of ecosystem services, and have higher levels of biodiversity (Sutherland et al., 2016; Thom et al., 2019). While the data in our study area indicate that areas already forested during the 19th century are less susceptible to natural disturbances, more structurally diverse old forests may be also better at maintaining ecosystem services after disturbances (e.g. with younger trees in lower layers of the canopy taking over after canopy disturbance). This suggests that for a resilient provision of ecosystem services, maintaining old forests should be prioritized over new afforestations (Körner, 2017). When new forests are established, their management should prioritise resilience (i.e., by promoting species' and structural diversity) in order to maintain their provision of ecosystem services in the long-term.

#### 4.3. Forest management implications

Intensifying forest management, e.g. through shorter rotation periods and intensified thinning regimes, has often been proposed as a way to mitigate the risk of natural disturbances in forests (Seidl et al., 2018; Zimová et al., 2020). However, our results indicate that prior forest management interventions may increase the forests' susceptibility to natural disturbances. This effect may be influenced, in part, by an autocorrelation in management records, where previously managed stands are more likely to be monitored and thus have a higher chance for disturbances to be recorded. However, we found a positive effect of recent management on disturbance susceptibility even when considering all non-anthropogenic satellite-detected disturbances, including events not reported in the management records. An opening in the stand due to felling may reduce local sheltering effects and the support that trees gain from their neighbours (Hale et al., 2012; Schelhaas et al., 2007), making them more susceptible to subsequent disturbances. In order to prioritize management interventions, it is thus crucial to identify situations when positive long-term effects of interventions on forest resilience are greater than the detrimental effects immediately after interventions.

While the available data did not allow for an analysis of long-term effects, our work provides some important indications on how forest management can promote structural and species diversity and decrease the risk of subsequent natural disturbances (Seidl et al., 2018). Our data suggest that management interventions in dense, homogeneous spruce stands would be most helpful at an early stage, before strong competition begins and tree crowns become relatively short (i.e. before the stem-exclusion phase, Bebi et al., 2013). Although such early measures that promote structural and species diversity are often not cost-effective in the short term (Temperli et al., 2017). However, positive effects of such interventions on diversity and disturbance risk may be much greater compared to interventions in later stages of stand development, when even-aged cohorts of trees are already susceptible, and an intervention may increase the risk of a disturbance instead of reducing it.

In this study, we only addressed one aspect of resilience, i.e. forests' resistance to disturbance. Other important aspects of resilience include the capacity of a system to maintain its function or rapidly return to a desired state after disturbance (Folke et al., 2004), as well as its capacity to adapt to change (Elmqvist et al., 2019). Over the long term, disturbances in vulnerable spruce-dominated stands can create more favourable conditions for other species (Zielonka et al., 2010), thus facilitating forests adaptation to climate change (Thom et al., 2017). Our study suggests that forest management may need to focus more on ensuring the required provision of ecosystem services, rather than attempting to reduce disturbance risk (Seidl et al., 2018). For example, while sanitary cuts after natural disturbance are a common practice aimed at reducing the risk of further bark beetle outbreaks, leaving woody debris in the forest may in fact help to maintain the protection function after disturbance (Teich et al., 2019; Wohlgemuth et al., 2017), as well as

supporting biodiversity (Wermelinger et al., 2017). A better understanding of spatial patterns of disturbance susceptibility as well as ecosystem service supply and demand (Strith et al., 2019) can help differentiate between areas where disturbance risk reduction is required, and those where embracing the natural disturbance regime may be more beneficial (Seidl et al., 2018).

#### 4.4. Limitations

In this study, we used a Landsat-based disturbance product and in-situ forest management records to derive a large spatially explicit dataset of natural and anthropogenic disturbances, which allowed us to investigate the drivers of different types of disturbances. However, this dataset has certain limitations. The detection of disturbances through remote sensing is limited to disturbances large enough to have a significant impact on the canopy at the scale of a Landsat pixel (30 m). This is reflected in the omission rate, where over 40% of reported management interventions (e.g., thinning) were not detected in the satellite data (see Table 2). Some small-scale disturbances that were not detected or reported may therefore be missing from our analysis, particularly in older and heterogeneously structured forests, where small-scale gap dynamics are typical (Panayotov et al., 2015).

The limitations of satellite data for detecting and identifying disturbances highlight the importance of complementing remote sensing with in-situ information (Senf et al., 2018). However, the mapping of forest management by practitioners is not always spatially accurate and, in some cases, only approximate point information is recorded for events. This creates uncertainty in matching the recorded management information to satellite-detected disturbances. As spatially explicit forest management records become more common, similar analyses may be possible with fewer uncertainties and over longer time scales in the future. In addition, it is important to note that while our dataset compiles the occurrence and agent of a disturbance, it does not contain information about the severity of the disturbance (e.g., percent tree mortality), which would be useful to better characterize the dominant disturbance regimes.

#### 4.5. Conclusions

In this study, we found that besides well-known factors such as topography and species composition, land-use legacies and recent management interventions affect the susceptibility of mountain forests to natural disturbances. In particular, closed spruce stands established after 1920 are more susceptible to natural disturbances than areas that were already forested during the 19th century. Our results also indicate that management interventions increase a stands' susceptibility to disturbance in the short term, highlighting the importance of considering trade-offs when managing mountain forests for resilience. In areas where a stable provision of ecosystem services is a priority, e.g. in protective forests, management interventions should take place early, before the stand reaches susceptible levels of canopy height and cover, since later management interventions may increase disturbance susceptibility. These findings also underscore the need to consider the interactions between site and stand conditions, land use and management history, and between different disturbance agents to improve our understanding of forest disturbance regimes.

#### CRedit authorship contribution statement

**Ana Strith:** Conceptualization, Formal analysis, Writing - original draft. **Cornelius Senf:** Data curation, Writing - review & editing. **Rupert Seidl:** Writing - review & editing. **Adrienne Grêt-Regamey:** Writing - review & editing, Supervision, Funding acquisition. **Peter Bebi:** Conceptualization, Writing - review & editing.



## 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 material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foreco.2021.118950>.

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