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Where to start with climate-smart forest management? Climatic risk for forest-based mitigation

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Abstract. Natural disturbances like windthrows or forest fires alter the provision of forest ecosystem services like timber production, protection from natural hazards or carbon sequestration. After a disturbance, forests release large amounts of carbon and therefore change their status from carbon sinks to carbon source for some time. Climate-smart forest management may decrease forest vulnerability to disturbances and thus reduce carbon emissions as a consequence of future disturbances. But how to prioritize stands most in need of climate-smart management? In this study we adopted a risk mapping framework (hazard × vulnerability) to assess the risk to climate-related forest ecosystem services (carbon stock and sink) in forests prone to windthrow (in the Julian Alps, Italy) and forest fires (in the Apennines, Italy). We calculated hazard by using forest fire and windthrow simulation tools, and examined the most important drivers of the respective hazards. We then assessed vulnerability by calculating current carbon stocks and sinks in each forest stands. We used these values together with the calculated hazard to estimate "carbon risk", and prioritized high-risk stands for climate-smart management. We show that combining disturbance simulation tools and forest carbon measurements may help in risk-related decision making in forests, and taking planning decisions for climate-smart forestry. This approach may be replicated in other mountain forests to help understanding their actual carbon vulnerability to forest disturbances.

1 Introduction

Natural disturbances are common phenomena in forest dynamics, disrupting forest cover, changing forest structure, and leading to forest succession (Dale et al., 2001). In Europe, disturbances like wildfires, windthrows, and insect outbreaks are increasing in frequency, intensity and severity due to changes in land use and climate (Lozano et al., 2017; Seidl et al., 2017; Sommerfeld et al., 2018; Collins et al., 2021; Senf et al., 2021; Senf and Seidl, 2021; Patacca et al., 2023; Grünig et al., 2023). In the future, forest fires may hit forests that were not previously endangered. Dry and warm weather and earlier snowmelt increase the risk of fires, which may affect new areas (Westerling et al., 2006). On the other hand, storm intensity will increase as an indirect effect of warmer and moister atmosphere, higher updraft velocities, and slower storm movement, increasing local duration (Kahraman et al., 2021). Such novel disturbance regimes may cause unprecedented changes over large scales that may alter the functioning of forest ecosystems and the provisioning of their services (Runkle, 1985). For example, bark beetle outbreaks

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or windthrow strongly decrease timber production and timber value, while forest fire may increase hydrological instability, alter habitats for forest biodiversity, and hamper recreation potential (Albrich et al., 2018). Additionally, regulating services, as e.g., carbon sequestration may be slowed down, stopped or even reversed, and the role of forests may change from sink to source for some time (Yamanoi et al., 2015; Pugh et al., 2019; Harris et al., 2021; Albrich et al., 2022).

Indeed, forests contribute to natural climate solutions by acting as the largest land carbon sink (Griscom et al., 2017), storing carbon in their biomass, soil and organic matter. Furthermore, they regulate the climate through influencing weather patterns, precipitation and contributing to local and global cooling. To counter the increasing risks posed by forest disturbances to such contributions, Climate-smart forestry (CSF) has been suggested as an approach that maximizes climate mitigation provided by the forest ecosystem and forest-wood products chain (Nabuurs et al., 2018). CSF aims to mitigate climate change through reducing the greenhouse gas emissions and increasing their sequestration, create more resilient forests by adaptive forest management, and increase productivity and the provision of other ecosystem services (ES; Nabuurs et al., 2018). Several case studies have shown the positive effects of CSF on climate change mitigation, even when considering trade-offs between different ES (Górriz-Mifsud et al., 2022; Gregor et al., 2022; Peltola et al., 2022).

One aspect of CSF is to foster adaptation to increased disturbances as wildfires and windthrows by promoting structural, physiological, and ecological determinants of forest resistance or resilience (Nabuurs et al., 2018), for example by increasing the degree of species mixture (Seidl et al., 2011). Other climate-smart strategies include selective thinning, changing forest rotation lengths, and promoting continuous-cover forestry (Verkerk et al., 2020). The effect of different disturbances in fact depends not only on the disturbance agent but also on the pre-disturbance forest structure (Vacchiano et al., 2016). Forest density, tree species composition, topography and soil properties influence the susceptibility to windthrow (Quine et al., 2021). In the case of wildfires, forest structure together with the amount of fuel and moisture affect forest flammability and the probability of fire spread.

The efficacy of climate smart forestry on regulating services can be assessed by calculating additional carbon sink, or avoided carbon emissions, as a result of additional management relative to current management. Within a growing conflict between higher demand for ecosystem services and increased disturbance risk, it is of great interest to understand the most effective forest management strategies to increase forest resistance and resilience and avoid or reduce disturbance-related emissions. However, assigning priorities for climate-smart forestry across whole forest catchments or ownerships might be difficult, given the multi-factorial nature of disturbance hazard and the different levels of ecosystem services provided by each forest stand under disturbance risk. In this study, we model the climatic hazard from windthrow and forest fire hazard in two Italian forests, we assess the vulnerability of forest carbon stock and sinks to these hazards, and calculate the climate risk for these important ecosystem services at the scale of individual forest stands. With this workflow, managers can prioritize high-risk stands for climate-smart management.

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2 Materials and methods

2.1 Study areas

We chose two study areas to proceed with our analysis, one for windthrow and one for forest fire hazard. Fusine study area is located in the Julian Alps, NE Italy (region of Friuli Venezia Giulia, Fig.1a). It is characterised by typical alpine climate, with high annual average precipitation of 1700 mm and mean annual temperature of 7° C. The studied area stretches from 750 m a.s.l. to 2200 m a.s.l. and the soil types are cambisols, leptosols and luvisols. The dominant tree species are Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*) and silver fir (*Abies alba*), and typical forest compositions here are: spruce-beech-fir, spruce, spruce-beech (the most common) and some stands of European larch (*Larix decidua*) and dwarf pine (*Pinus mugo* subsp. *mugo*; Fig. 1b). Forests at Fusine have provisioning ES valuable for its timber production, but also cultural service as the lakes of Fusine are an important touristic destination. Some of the forest fulfil protective function against natural hazards. Fusine forest is managed as high forest governance. The prevalent management here is the shelterwood system in groups and the single-tree selection cutting in uneven aged forests. Thinning from below in young forests is executed to favour the dominants (De Crignis, 2020).

Galeata study area is situated in the northern Apennines, Italy (region Emilia-Romagna, Fig.1a). It has temperate oceanic sub-Mediterranean climate with low precipitation of about 630 mm and an average temperature of 12° C per year. The forest grows from the valley bottom at 300 m a.s.l. to the mountain tops of around 1000 m a.s.l. The prevalent soil types are cambisols and regosols. At Galeata, tree species composition varies between different types of forest stands (Fig. 1c). There are coppice stands with tree species like hop-hornbeam (*Ostrya carpinifolia*), pubescent oak (*Quercus pubescens*), manna ash (*Fraxinus ornus*) or Turkey oak (*Quercus cerris*), protection forests of conifer afforestation with spruce, black pine (*Pinus nigra*) and Scots pine (*Pinus sylvestris*), and coppice stands in transition or high forests of hop-hornbeam, pubescent oak, chestnut (*Castanea sativa*), European beech, Italian maple (*Acer opalus*), field maple (*Acer campestre*), manna ash, true service tree (*Sorbus domestica*), wild service tree (*Sorbus torminalis*), whitebeam (*Sorbus aria*), wild cherry (*Prunus avium*) and Douglas fir (*Pseudotsuga menziesii*). Forests at Galeata have an important regulating ecosystem service, protecting against soil erosion and regulating water supply. Additionally, they contribute to the cultural function for recreation and tourism. Forest management especially aims to reduce the fire risk by improving the state of the current coppice stands and converting some of them to high forests. In high forest stands (especially in the conifer afforestations) usual thinning operations are implemented.

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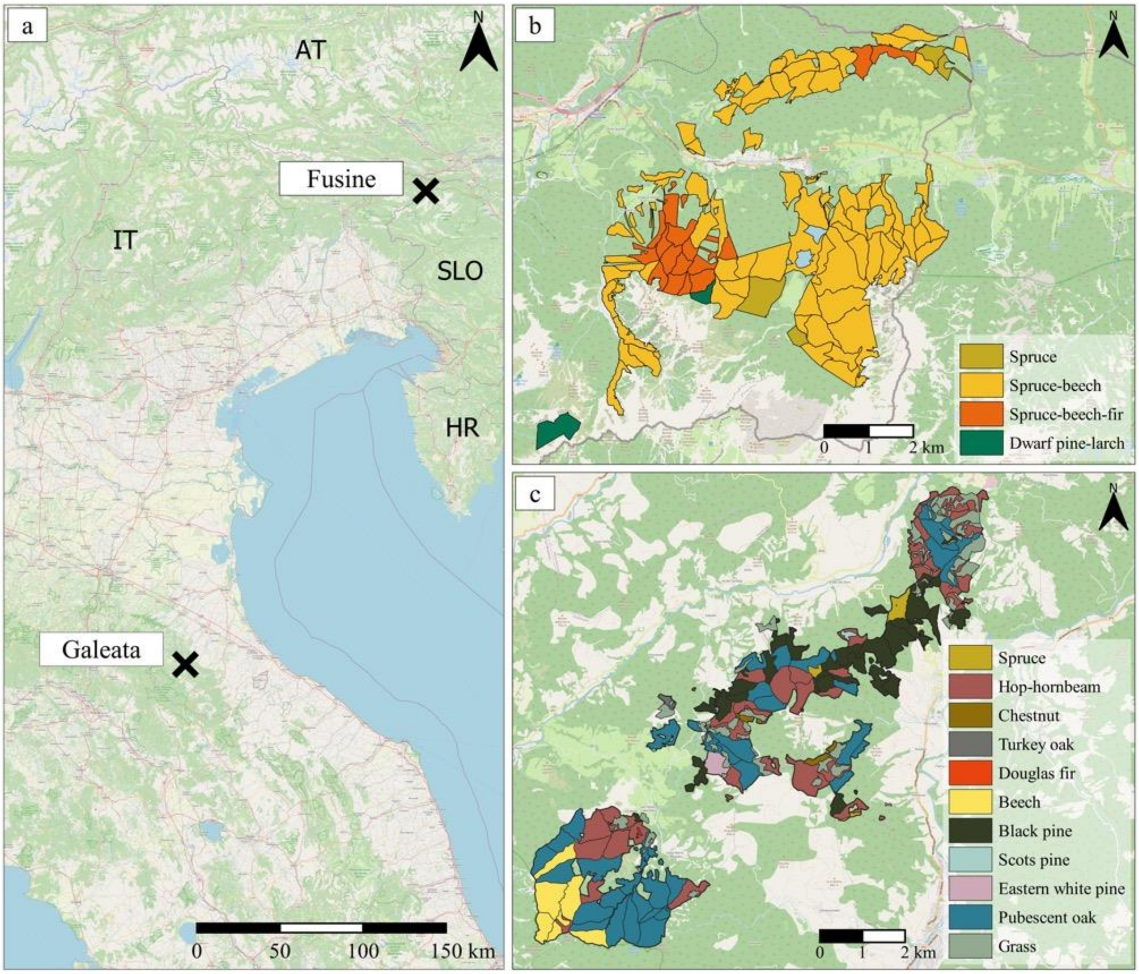

Figure 1: (a) Location of the study areas Fusine (Friuli Venezia Giulia) and Galeata (Emilia-Romagna). (b) Fusine represents typical montane to alpine forests stands in the Alps with dominating species spruce and beech. (c) Galeata has very heterogeneous forest stands from coppice dominated by broadleaves like hop-hornbeam and pubescent oak to conifer afforestation with pine and spruce. Base map: © OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

2.2 Field sampling

We measured forest structural parameters in 23 forest management units in Fusine and 45 in Galeata; the number of units to sample was decided to represent in the best way the dominant forest types. For every unit, we randomly established a circular sampling plot with 10 m radius. (QGIS Development Team, 2009). We measured diameter at breast height (DBH) of all trees within each plot, total height and crown base height of three individual trees for each tree species and diameter class (<15 cm, 15-30 cm, >30 cm). These trees were also sampled with an increment borer to estimate tree age and the width of the last ten annual rings from the increment core.

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We carried out a sampling campaign to obtain the data on fuel loads at Galeata. We applied a standard scheme (Bovio and Ascoli, 2013) establishing two random sampling sites in each of four main forest types. Three transects of 10 m in form of an equilateral triangle were arranged at each site, with the following data being measured every 1 m of the transect: shrub height, height of herbaceous layer, forest litter thickness, and humus thickness. All pieces of coarse deadwood (2.5 – 7.5 cm in diameter) were counted if they intersected with the transect line. We calculated the total amount of coarse deadwood in t/ha using the following equation (1):

$$V = \frac{1.234 \times n \times d^2 \times a \times c}{L}, \tag{1}$$

where V is the volume expressed in m^3ha^{-1}, 1.234 is a constant, n is the number of counted intersections, d is the mean diameter of the class (i.e., 5 cm), a is a correction factor of 1.13 for diameters smaller than 7.5 cm, c is the correction factor of the slope of the transect (Brown et al., 1982), derived from this equation (2):

$$c = \sqrt{1 + (\frac{\alpha}{100})^2}, \tag{2}$$

where α is the slope inclination of the measured transect in % (Brown et al., 1982). The slope was extracted from an available digital terrain model (DTM).

Using the number of shrubs intersecting the transect we calculated shrub abundance per hectare. Using the shrub height recorded on field we calculated the DBH by using the following equation (3):

$$DBH = a1 + e^{\frac{\ln(H) - \ln(b1) + b2 \times \ln(a2)}{b2}}, \tag{3}$$

where H is the shrub height and a1, a2, b1 and b2 are species-specific coefficients (Evans et al., 2015). Individual shrub biomass was then obtained by applying species-specific allometric equations (Jenkins et al., 2004; Albert et al., 2014) that use height and DBH. The individual biomass was then multiplied by shrubs density to obtain the per-hectare shrub loads.

In addition, three samples of duff, litter, live herbs, live shrubs, and fine deadwood (0.6 – 2.4 cm in diameter) were collected in squares of 40 × 40 cm located at the centre of each side of the triangle. These samples were oven-dried in a laboratory at a temperature of 105 °C for 24 hours and finally weighed. Dry fuel loads were then averaged per plot and scaled on a per hectare basis.

2.3 Disturbance hazard

2.3.1 ForestGALES

We chose ForestGALES to simulate windthrow at Fusine, as a function of topography, forest structure and soil parameters. The critical wind speed (i.e., minimum wind velocity sufficient to cause breaking or overturning) was used as a proxy for the windthrow hazard. ForestGALES (Locatelli et al., 2017) calculates the probability of windthrow damage to individual trees and forest stands, as a function of tree species, height, DBH, rooting depth (shallow/deep), topography, soil type, and current tree spacing. Topographic exposure (TOPEX) was calculated from a digital terrain model (DTM, 1 m resolution) and averaged across each forest stand. Tree and forest variables were calculated from field measurements and gap-filled with up-to-date data from existing forest plans (validity 2021-2035; De Crignis, 2020). Soil type was derived from the soil map of Italy with a scale of 1:100000 (L'Abate et al., 2015). ForestGALES calculates the critical wind speed at which trees could be damaged by uprooting or stem breakage. We calculated a synthetic windthrow hazard indicator by averaging the critical windspeed at 1.3 m height and at crown height for breaking and for overturning. For two-species stands, simulations had to be performed for each tree species separately in order to obtain species-specific critical wind speeds. Critical wind speed for the whole stand was then calculated as a weighted average, using weights proportional to the relative contribution of each species to the number of trees in each stand.

In order to analyse the role of forest parameters in influencing the vulnerability of forest stands to windthrow, we performed a multiple linear regression of average critical windspeed as a function of tree density, number of trees, relative species composition by volume, DBH, tree height, and height to DBH ratio. We used the gamma distribution since the values for critical wind speed are strictly positive. We excluded larch and Scots pine stands because of their small sample size. Since the share of beech was correlated to the share of spruce, we included only beech data in the final model. We performed model selection using AIC-based stepwise backwards selection.

2.3.2 FlamMap

We assessed fire hazard using burn probability (i.e., the likelihood of future fire occurrence) considering topography, fuel loads and weather using the simulation tool FlamMap. The FlamMap (Finney, 2006; Stratton, 2006) fire mapping and analysis system calculates fire behaviour characteristics (e.g., rate of spread, flame length, fireline intensity) and burn probability for surface and crown fire for each pixel within the landscape, based on topography, moisture, weather, forest structure, and fuel conditions, provided each as a raster layer, and a vector layer with user-defined ignition locations. Slope, elevation, and aspect were extracted from a digital terrain model (DTM) and resampled at 10m resolution. The main weather variable required by the simulations is wind, for which we used a software feature from FlamMap called "Wind Ninja" that uses weather and geographical information to calculate a raster of wind direction and speed for the whole study area. The input data included air temperature (Zepner et al., 2021), cloud cover (personal communication from local expert), longitude, and time zone. Input data on forest structural parameters include tree heights, crown base height, and tree cover density. Species-specific, third-degree polynomial regressions were fitted between DBH and height and between height and crown base height measured in the field. We calculated tree height and crown base height for all trees in each plot, and averaged them to obtain estimates for each measured forest management unit. For unmeasured forest units, we filled in the average tree heigh and crown base height calculated from all other plots in the study area belonging to the same forest type. All 10 m within each forest management unit were ten assigned the same values of forest structural variables. Tree cover density was estimated from the High-resolution Copernicus layer on Tree Cover Density 2018, with a grain of 10 m (European Environment Agency, 2020).

Fuel data must be provided in the form of standard fire behaviour fuel model (Scott and Burgan, 2005); fuel loads measured in the field for five load components (1h – duff and litter, 10h – fine woody debris, 100h – coarse woody debris, live herbaceous, and live shrub fuels) were compared to fuel loads of standard fuel by Scott and Burgan (2005) to assign the closest-

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matching fuel model to each landscape pixel, at the resolution of 10 × 10 meters. For other forest types that were not included in the field sampling, we used a surface fuel dataset for Italy (Ascoli et al., 2020). The fuel loads were compared to the standard fuel models, and associated with the standard model that best reflects the characteristics measured. The degree of humidity was set to low as we intended to simulate a rather extreme fire weather scenario.

As a wildfire hazard indicator, we chose burn probability (BP), which has been widely used in assessing wildfire hazard in forest management plans (Benali et al., 2021). To calculate the burn probability, we instructed the software to generate 500 random ignitions points in the study area and we set the maximum simulation time in 10 hours.

We then modelled BP as a function of FlamMap input data, to find the most important drivers of fire hazard. As many input variables were collinear, we decided to use regression trees to recognize the most important variables. We included the following input parameters: forest type (coniferous/broadleaves), tree height, crown base height, canopy bulk density, crown cover, elevation, aspect (cosine-transformed) and slope.

2.4 Vulnerability and risk of carbon stocks and sinks

We used allometric methods in order to calculate the amount of carbon stocked at the two study areas. Using DBH and tree height collected from field measurements and forest management plans, we calculated aboveground tree biomass using species-specific allometric equations for Italy (Tabacchi et al., 2011). Biomass was converted into carbon stock using a carbon density value of 0.47. We then estimated belowground, deadwood, litter and soil carbon using empirical equations from the Italian National Forest Inventory (Vitullo et al., 2007).

In order to calculate carbon sink, we used the increment cores collected in the field. Cores were mounted and sanded in the lab following standard dendrochronological methods, then scanned for subsequent analyses. We measured the total width of the last ten rings of each tree core using CDendro and CooRecorder (Cybis Elektronik & Data AB). We converted diameter increment into DBH and tree height time series using previously fitted DBH-height equations, and then to aboveground biomass and carbon increment per decade by applying allometric equations.

In order to evaluate the risk, i.e., the product of hazard and vulnerability, we rescaled the values for windthrow/fire hazard and carbon stocks and sinks from 0 to 1. The windthrow hazard was expressed in terms of critical wind speed, where the lowest values led to higher probability of windthrow hazard and therefore had to be rescaled from 1 to 0. The vulnerability of carbon stock and sink to either a windthrow or wildfire hazard was calculated as the product of rescaled hazard value and rescaled vulnerabilities (carbon stock and sinks). The highest values indicate the highest vulnerability for carbon stock or sink to windthrow or wildfire damage, for a total of four risk maps.

For all statistical analyses we used R software version 4.2.1 (R Core Team, 2022) together with RStudio version 2023.09.0 (RStudio Team, 2020). The visualisation was performed using the R package *ggplot2* (Wickham, 2016).

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3 Results

3.1 Windthrow simulations

The simulated critical wind speeds varied between 5.3 to 25.2 m s^{-1} with a mean critical wind speed of 15.6 m s^{-1} for the entire study area of Fusine. Greater values for wind speed mean greater ability of forest to withstand a windthrow. The lowest critical wind speeds indicate the most vulnerable forest stands. The lowest values were found to be below 10 m s^{-1} (Fig. 2), which is probably due to lower densities and high slenderness in the respective forest stands.

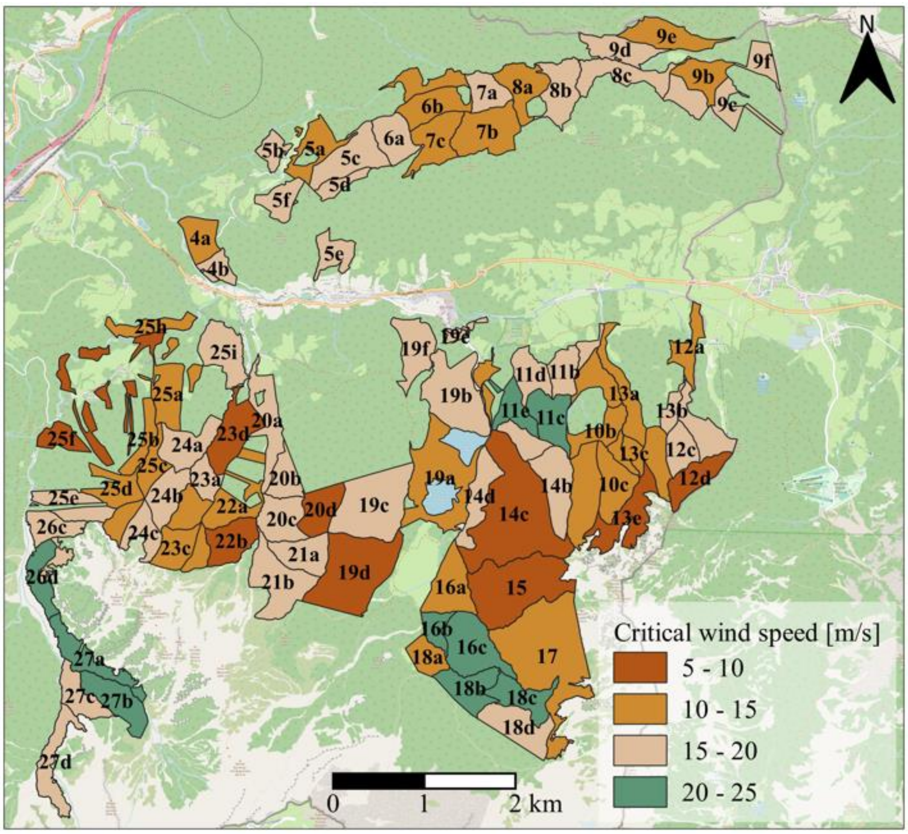

Figure 2: Critical wind speeds in m s^{-1} simulated by ForestGALES at Fusine. The lowest wind speeds show highest vulnerability to windthrow (dark brown). Base map: © OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

Density, share of beech (volume percentage), tree height and slenderness (ratio between height and DBH) were important variables affecting the windthrow hazard (Table 1). More beech compared to spruce resulted in higher critical wind speed (Fig. 3). Furthermore, increasing density and lower slenderness led to higher critical wind speed, meaning less vulnerable and more stable forest stand.

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210 **Table 1: Results of regression analysis with gamma distribution to predict the critical wind speed at Fusine.**

	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	-4.441e-02	1.435e-02	-3.094	< 0.01
Density	-3.970e-05	5.513e-06	-7.201	< 0.001
Share of beech	-3.237e-02	4.039e-03	-8.013	< 0.001
Tree height	-8.280e-04	3.751e-04	-2.207	< 0.05
Slenderness	1.656e-01	9.092e-03	18.212	< 0.001

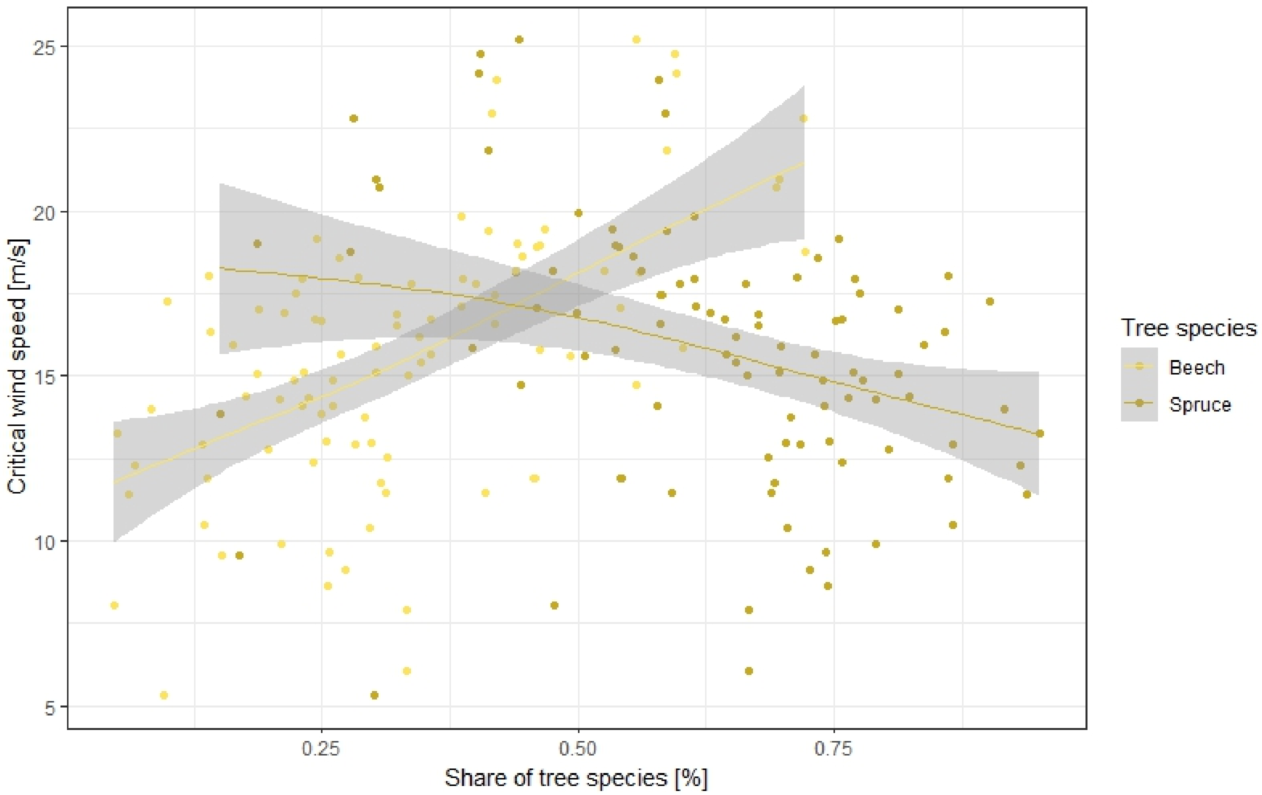

Figure 3: Critical wind speed increases with higher stock of beech within a forest stand. Higher share of spruce increases the vulnerability to windthrow.

3.2 Forest fire simulations

215 Fuel loads measured in the field differed in the main forest types (Table 2). The depth for pine forest type were similar as in the hornbeam, but the fuel loads were lower with an exception of herb layer that was higher in pine forest type. Pubescent oak had the highest values of fuel loads for 1-h, 10-h and shrub layer. Spruce forest type reached lowest values in the depth of the overall flammable layer and fuel loads for duff, herb and shrub layers.

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We chose three standard models to represent the forest types at Galeata that were compared to the calculated fuel loads and 220 the surface fuel dataset (Table 3 and Table A1 in the Appendix).

Table 2: Fuel loads that were manually calculated from the sampling campaign for the main forest types.

Forest Type	Depth (cm)	Fuel load (t ha^{-1})					
		Duff	1-h	10-h	100-h	Herb	Shrub
Pubescent oak	9.54	11.95	8.48	2.60	3.94	0.59	1.60
Hornbeam	10.83	16.44	5.36	2.46	7.86	0.95	0.75
Pine	10.48	11.96	5.06	1.05	2.79	3.29	0.15
Spruce	6.49	6.06	7.42	2.48	8.65	0.19	0.06

Table 3: Association between forest types in Galeata and the standard fuel models from Scott and Burgan (2005)**.**

Forest Type	Associated Standard Fuel Model
Pubescent oak	164
Hornbeam	164
Pine	186
Spruce	186
Chesnut	165
Turkey oak	164
Douglas fir	186
Beech	164

225

The burn probability varied across different forest stands at Galeata and was highest in north of the area (Fig. 4). Forest stands that are more prone to fire were dominated by pubescent oak and hop-hornbeam.

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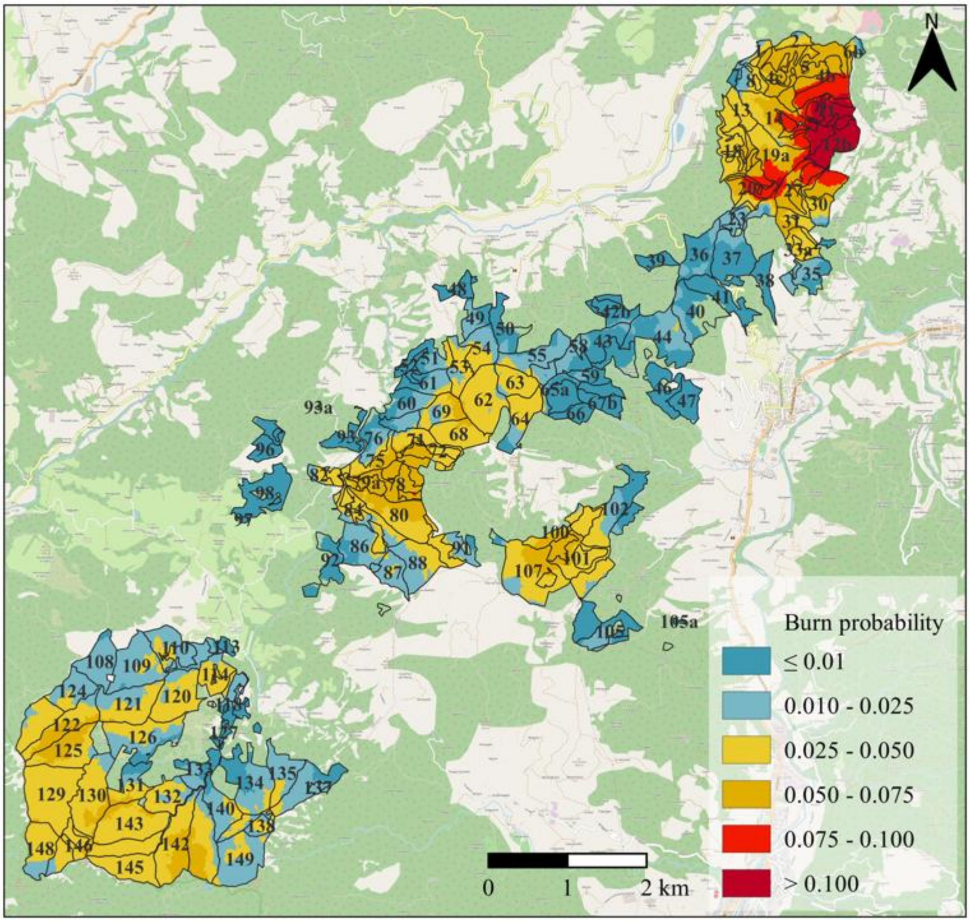

Figure 4: Simulation results of burn probability from FlamMap. Base map: © OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

From the regression tree it's visible that the most important factor in determining the burn probability is the forest cover type (coniferous/broadleaves; Fig. 5). In the forest stands with coniferous dominant tree species (pine, spruce or Douglas-fir) the calculated fuel loads were the lowest, so the fire hazard was lower compared to the broadleaved-dominated forests. Moreover, the elevation and aspect were important parameters influencing the susceptibility to fire, making forests at lower elevations and at slopes with aspects from east through south to west more susceptible. Higher crown cover further increases the burn probability as denser crowns spread potential crown fire faster, and also produce more litter in the forest floor.

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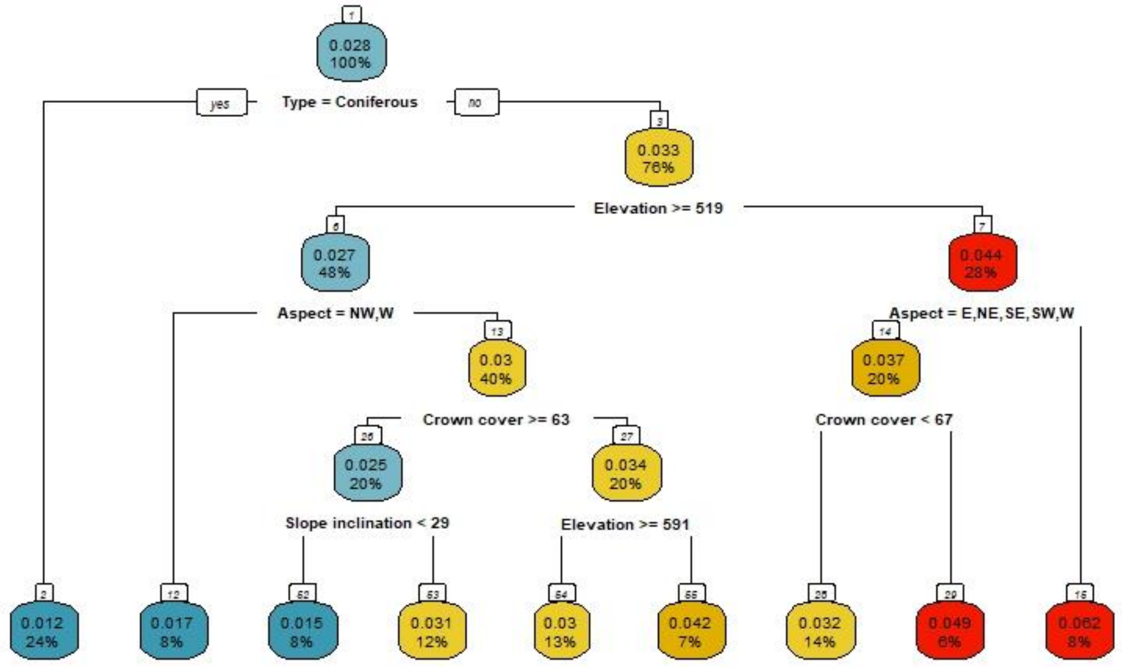
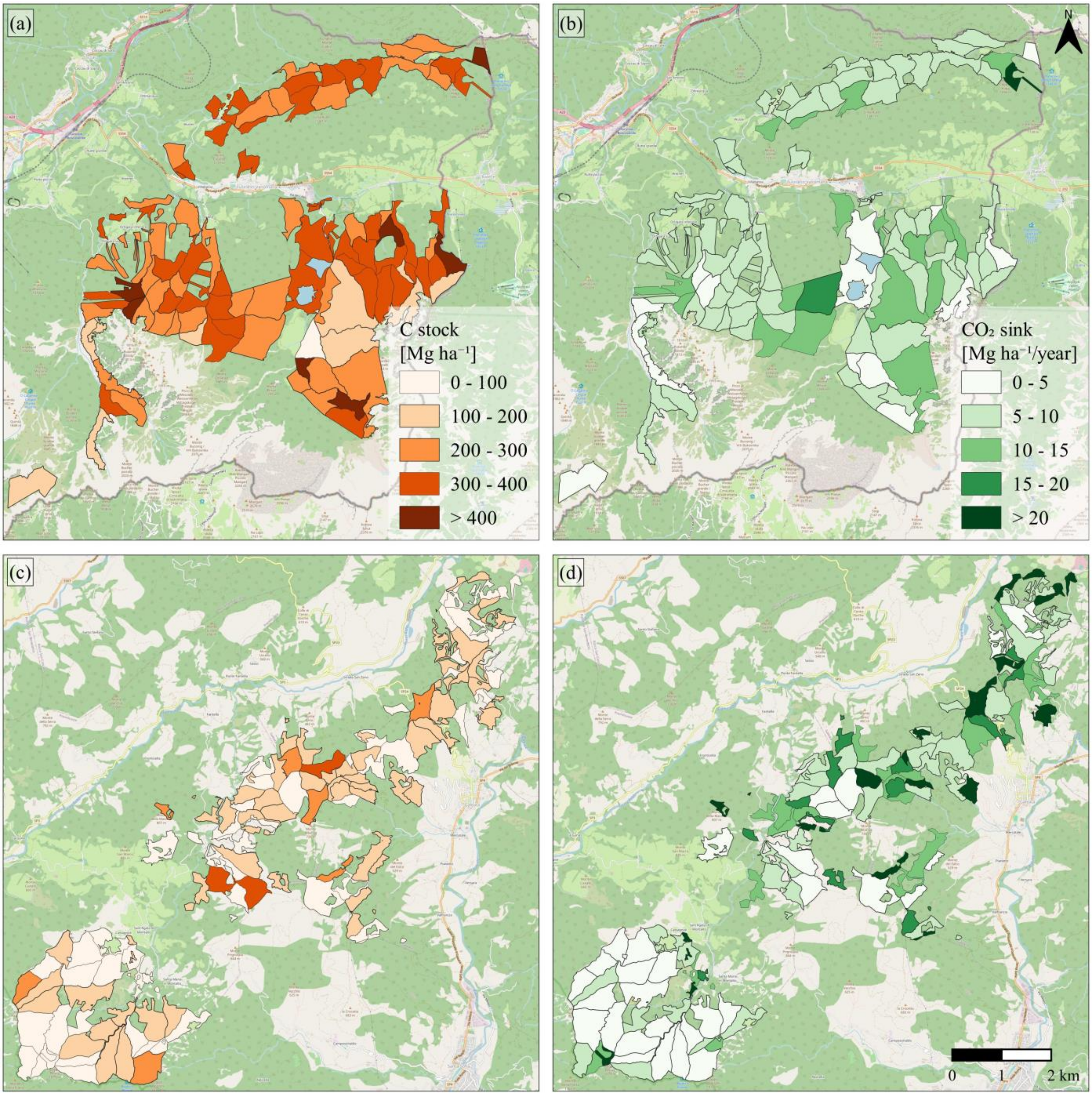


Figure 5: Regression tree to predict the burn probability at Galeata. Nodes 2 and 3 were formed by splitting node 1 on the predictor variable *Type*. Node 2 consists of all rows with the value of *Type* = coniferous (24%) and node 3 consist of all rows with *Type* = broadleaves (76%). Next nodes are *Aspect, Crown cover, Slope inclination* and *Elevation*.

3.3 Carbon stock and sink

The amount of carbon stock and sink varied by study area and management units (Fig. 6). The C stock at Fusine was greater compared to Galeata, but the C sink reached overall higher values at Galeata. The average carbon stock and CO_2 sink were 302 Mg ha^{-1} and 9 Mg ha^{-1}/year at Fusine and 115 Mg ha^{-1} and 15 Mg ha^{-1}/year at Galeata.

The final maps of carbon risk are reported in Figure 7. More vulnerable forest stands shown in darker colours and are a result of either high disturbance hazard (windthrow or wildfire) or high vulnerability of carbon stock/sink, or a combination of both.



250 **Figure 6: The amount of C stock at Fusine (a) and Galeata (c) and CO_2 sink at Fusine (b) and Galeata (d). Base map: © OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.**

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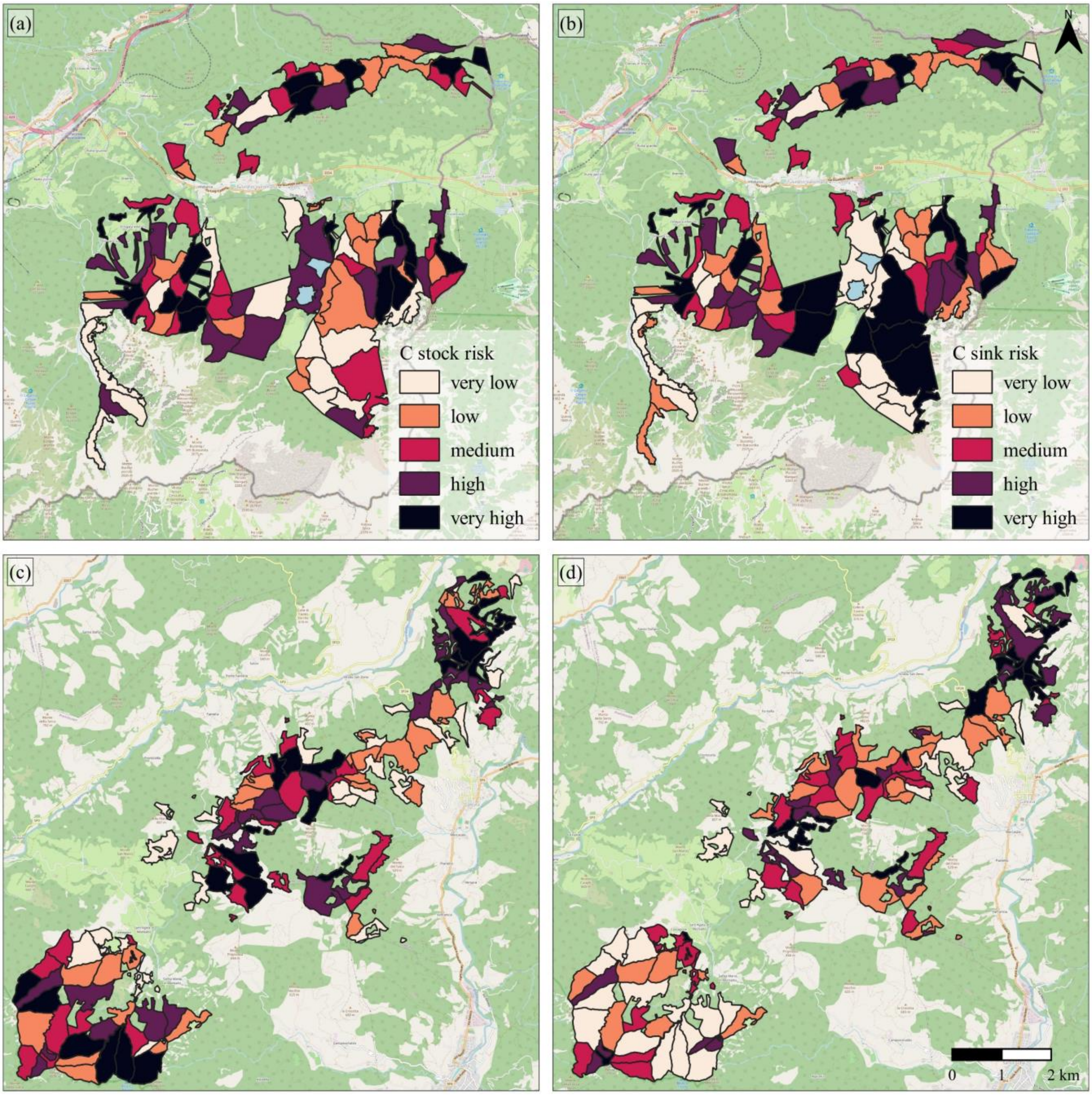

Figure 7: The calculated risk to C stock (a) (c) and sink (b) (d) at the two study areas Fusine and Galeata. The darker the colour, the higher the risk. The C risk was calculated as the product of the amount of C stock/ CO_2 sink and the exposure to either windthrow or wildfire. The legend shows classes equally distributed by quantiles. Base map: © OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

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4 Discussion

4.1 Disturbance-related risk for carbon stocks and sinks

Risk assessment and prevention for fire or windthrow hazard focuses on the human component of vulnerability. However, forest ecosystem services (ES) of interest to society should also be considered as vulnerable assets, such as climate change mitigation (this can be generalized to, e.g., hydrogeologic protection or recreational value). In this study, we have coupled state-of-the-art forest disturbance simulation tools with quantitative assessment of forest carbon stocks and sinks to prioritize risk prevention strategies in mountain forests. Climate-smart forestry may help to reduce forest disturbances leading to mitigation of carbon loss. The combination of the results of the hazard analysis together with the vulnerability to carbon allowed to identify forest stands with higher carbon risk. In these areas it was thus suggested to carry out proper silvicultural interventions. Prevention silviculture aims to enhance those characteristics of forest stands that allow increasing the resistance and resilience of forests to the hazards analysed, and consequently minimizing the loss of ES. Different management strategies together with future climate will affect the temporal stability and the level of ES provisioning. However, in case of increased temporal stability of ES, the level of ES provisioning may be lowered, so an acceptable trade-off should be found for each local case (Albrich et al., 2018).

Data collection for simulating the provision of various ES may be based on different data sources from fieldwork or existing forest management plans as in our study, or from available digital data like vegetation height models, digital terrain or surface models (Brožová et al., 2020, 2021), or other data derived from remote sensing. Such data vary in resolution based on the platform and sensor used, and they provide information on crown coverage, canopy gaps, surface roughness, tree height and other forest structural parameters. Moreover, such parameters may be used to simulate disturbance severity and probability of occurrence, and also expected forest growth using models of forest dynamics. These models are useful to assess the impacts of climate change or different management scenarios on future levels of ES (Albrich et al., 2018), and to quantify carbon amounts "saved" by preventive silviculture as discussed in this paper.

Our methodology calculates carbon risk as a combination of disturbance hazard analysis together with carbon stock and sink exposure. Forest disturbance may be simulated using hybrid-mechanistic models (like here used ForestGALES and FlamMap models) or statistical models, such as machine learning (Hart et al., 2019; Pawlik and Harrison, 2022). Statistical models require information on observed damage and are therefore not suitable if this kind of data is not available. We showed that hazard modelling can be a valuable support to forest planning and management in order to maintain or improve the provision of ecosystem services. However, simulation tools for disturbance hazard assessment may not be easily used by forest practitioners. Therefore, we analysed the most predicting parameters for windthrow and wildfire hazards. Forest parameters for both disturbance hazards may be easily obtained from databases like forest management plans or available digital elevation models. For windthrow hazard, structural parameters like density, tree height and slenderness, together with species composition were found to be the most important determining the vulnerability. Denser and taller forests with higher slenderness and higher share of spruce led to lower critical velocities, i.e., a higher probability of windthrow. With an

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increasing tree height, there is a corresponding increase in the force exerted on the tree at a given wind speed. This increased susceptibility to force makes taller, slender trees more prone to windthrow. Indeed, slenderness is one of the most frequently used indicators to estimate the stability of trees to strong winds (Hanewinkel et al., 2013). Analysis of satellite images supports our results, where natural disturbance like windthrow and bark beetle outbreaks occurred mainly in denser spruce forests (Stritih et al., 2021). In a study from Germany, tree height and tree species were the most important predictors for windthrow damage. Similar to our research findings, also here the coniferous species like Norway spruce was the most vulnerable tree species (Albrecht et al., 2012). Wildfires were in our case best predicted by forest type (coniferous/broadleaves), elevation, aspect and crown cover. Different forest types influence the probability of fire through various fuel content and also different amounts of moisture. Southern and western aspects have warmer and drier conditions due to more sun rays during the day and are thus more fire-prone compared to other aspects (Pandey and Ghosh, 2018). Likewise, meteorological factors influence the probability of forest fire significantly, especially temperature and relative humidity (Zhang et al., 2023b). Using these forest parameters together with past event documentation may help forest practitioners to better identify the spatial extent of hazard in the mountain forests.

Mountain forests are more efficient in carbon sequestration in comparison to lowlands, despite the overall low sequestration rates compared to the anthropogenic carbon production (Schirpke et al., 2019). In case of disturbance, the in-situ C sink may shrink (Lindroth et al., 2009) or even turn to C source (Albrich et al., 2022; Yamanoi et al., 2015). Our methodology provides a good basis for calculation of forest carbon scenarios in case of improved forest state and thus a decrease in forest damage in the future. Furthermore, it is possible to use our data to calculate the amount of carbon credits that may be generated in the respective areas.

Finally, carbon loss mitigation is an important aspect of disturbance avoidance, but maintaining other ecosystem services may be just as important in the future. Mountain forests provide a variety of ES, both globally and locally, like protection against natural hazards, provision of drinking water, food and forage (Schirpke et al., 2019). Timber production has been historically one of the most important forest functions – it provided people with building material and energy source. Wood as building material is coming back to the focus as it provide a sustainable product substitution and a possible improvement of forest carbon sinks (Kauppi et al., 2018).

4.2 Priorities for Climate Smart Forestry

In forest stands that were most prone for windthrow or wildfire, i.e., had the lowest critical wind speeds (Fig. 2) or the highest burn probability (Fig. 4) and the highest amount of carbon stock (Fig. 6), management interventions were proposed. The objective in windthrow-prone forests is to improve the resistance characteristics of forest stands to increase the critical wind speed causing breakage or overturning. The management practice includes: avoidance of unstable edges prone to higher wind speeds; selective thinning of individuals with deeper canopy and better anchorage; thinning for increasing growth and stability, and reducing natural mortality of individuals; increasing structural (horizontal and vertical), age and species diversity. We proposed an increased species diversity at Fusine, where unstable spruce-dominated forests may be regenerated with

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broadleaved species to aim for better stand stability (Nabuurs et al., 2018). Tree height may be decreased by shortening the rotation length (Albrecht et al., 2012), which also leads to a reduced probability of windthrow damage (Potterf et al., 2023). Furthermore, thinning operations, increased structural and age diversity, and avoidance of unstable edges were recommended. Such management strategies lead to higher temporal stability of ecosystem services provisioning as e.g., the C stock or timber volume (Albrich et al., 2018).

In case fire-prone forests, the aim is to reduce the flammability of stands through reduction of fuel load and continuity, with the purpose of modifying fire behaviour to reduce the intensity of an eventual fire and the consequent loss of stand. The possible forest interventions include: opening of discontinuities to have more air flow and thus greater heat loss; selective thinning with larger diameters and with higher crown insertion; reducing the density and size of individual tree groups; reducing the amount of shrub and deadwood to decrease the rate of spread and intensity of the flame, and to prevent fire spread from the ground to the crowns. Similarly, we proposed management in forest stands at Galeata with further management of continuous forest cover by segregating these. Some of the common climate smart forestry practices in wildfire-prone areas include thinning and removal of excess fuel, e.g., through prescribed fire. Such practices may improve the health of the forest and its ability to resist and increase the resilience to face extreme weather events (Nabuurs et al., 2018). Thinning decreases canopy cover and tree density as well as competition, thereby increasing the availability of resources such as ground light radiation, water and nutrients and consequently, in proportion to the intensity of the intervention, more vigorous growth of the remaining individuals (Pretzsch, 2005). Furthermore, thinning operations increase woody increment, especially with higher intensities (Bianchi et al., 2010). The difference in increment may reach up to 20-30% more compared to non-thinned forest stands (Kim et al., 2016). As a direct consequence of increased growth increment, thinning allows stands to absorb more carbon from the atmosphere (Collalti et al., 2018). Comparing the carbon stocks 30 years after thinning with different intensities, no change in biomass has been observed and thus no difference in carbon stocks (Erkan et al., 2023). Thinning operations in secondary forests increased the tree diversity, which was positively correlated with carbon storage (Zhang et al., 2023a). These findings may bring good arguments for managing forest for an increased stability and biodiversity, making them more resilient and resistant to forest disturbances with no cost in the future biomass yields.

5 Conclusions

Implementing climate-smart forestry practices can play a crucial role in minimizing forest disturbances and, consequently, mitigating carbon loss. By integrating hazard analysis outcomes with carbon vulnerability assessments, it becomes possible to pinpoint forest stands at an elevated risk of carbon loss. In these identified areas, strategic silvicultural interventions are recommended to address and manage the potential carbon risk effectively. We thus propose a methodology that combines simulating disturbance hazard and forest carbon exposure, which may help in risk-related decision making in forests, and taking planning decisions for climate-smart forestry. This approach may be replicated in other mountain forests to help understanding the actual carbon vulnerability to forest disturbances.

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Code and data availability

Code and data are available from the corresponding author on request.

Author contribution

NP performed the statistical analysis and wrote the manuscript. LM performed the fire hazard simulations and wrote the manuscript. EN supervised the fieldwork, performed the analysis and wrote the manuscript. GV conceptualised the research, defined the research structure, wrote and reviewed the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Appendix

545 **Table A1: Fuel models chosen to represent forest stands at Galeata to simulate burn probability with FlamMap and the respective area with the respective standard fuel model.**

Standard Fuel Model	Fuel Model Code	Fuel Model Name	Fuel load (t ha^{-1})					
			1-h	10-h	100-h	Herb	Shrub	Area (ha)
164	TU4	Dwarf Conifer with Understory	10.09	0	0	0	4.48	1484.45
165	TU5	Very High Load, Dry Climate Timber-Shrub	8.97	8.97	6.73	0	6.73	16.93
186	TL6	Moderate Load Broadleaf Litter	5.38	2.69	2.69	0	0	444.47