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Vulnerability of European forests to natural disturbances

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Contents

Executive summary

European forests provide a set of fundamental services that contribute to climate change mitigation and human well-being. At the same time, forests are vulnerable systems because the long life-span of trees limits the possibility of rapid adaptation to drastic environmental changes. Climate-driven disturbances in forests, such as fires, windstorms and pests (e.g. insects), are expected to rise drastically under global warming. As a result, key forest services, such as carbon sequestration and supply of wood materials, could be seriously affected in the near future. Despite the relevance and urgency of the issue, little is known about the vulnerability of European forests to multiple climate-related hazards.

To fill this knowledge gap we investigated the susceptibility of European forests when exposed to a given natural disturbance. For this purpose, we assessed forest vulnerability by integrating in a data-driven framework satellite observations, land surface climatic data and records of disturbances over the 2000-2017 period. The integration of these data streams is meant to capture the key drivers of vulnerability and to quantify, for the first time, the vulnerability of European forests to fires, windstorms and insect outbreaks in a systematic and spatially explicit manner. We point out that, the term vulnerability is used in this study to express to what degree a forest ecosystem is affected when exposed to a given disturbance. In order to derive risk estimates, vulnerability estimates should be integrated with hazard and exposure components, according to typical impact assessment frameworks.

Results of this analyses show that in average at Europe level forest vulnerability to windstorms appears to be the disturbance with larger biomass loss both in relative and absolute terms (~38%, ~17 t ha^{-1}) compared to fires (~24%, ~12.5 t ha^{-1}) and insect outbreaks (~21%, ~9 t ha^{-1}). Substantial spatial variations in vulnerability emerge and exhibit generally higher values in northern and Mediterranean regions. Overall, forest structural properties play a larger role on the vulnerability of European forests to natural disturbances compared to climate and landscape features. However, increases in temperature and changes in precipitation patterns that occurred over the last two decades have substantially contributed to make European forests more vulnerable to natural disturbances. We found that these changes in climate led to a negligible increase in vulnerability in Europe to fires and windstorms and to a strong increase to insect outbreaks. However, contrasting regional trends emerging over Europe mask relevant temporal changes in vulnerability occurring at local scale. When analyses of single disturbances are combined together, results show that large parts of the European forests are substantially vulnerable to at least one natural disturbance and that many of the highly vulnerable areas have been subject to a further amplification over the observational period due to changes in climate.

Previous assessments of future climate risks to European forests, based on catalogues of disturbances collected at country level, have shown that damage from fires, windstorms and insect outbreaks is likely to increase further in coming decades. Such intensification could offset the impact of land-based strategies aiming to increase the forest carbon sink or other ecosystem services. However, the country scale approach used in such studies does not allow to explore in detail the underlying physical processes and to elaborate forest adaptation strategies at appropriate local levels. It is therefore fundamental to elaborate new modelling approaches that address in an explicit manner the high spatial and temporal variability of forest disturbances. In this respect, machine learning approaches and the increasing availability of multi-platform satellite observations of land surface represent valuable opportunities to appraise the impact of forest disturbances at a spatial and temporal resolution relevant for forest management strategies. This explorative study represents a first step towards such integrated framework.

1. Introduction

European forests cover more than 2 million km^2 or 33% of the land surface (Forest Europe, 2015) and provide a set of essential services that contribute to human well-being and climate mitigation. Unfortunately, forests must increasingly cope with an intensification of climate stressors. This exposes forest ecosystems to unprecedented environmental conditions outside the ranges in which they originally evolved. These changes occur too fast for evolutionary adaptation processes to keep pace (Seidl et al., 2017; Trumbore et al., 2015). Natural disturbances - large pulses of tree mortality that originate from climate-related abiotic and biotic agents such as fires, strong winds or insect outbreaks (Seidl et al., 2014) - represent serious peril for maintaining healthy and productive forests. The vulnerability of forests to such natural disturbances is a key determinant of risk and reflects the propensity of a forest to be adversely affected when exposed to hazardous events (IPCC, 2014). In its turn, vulnerability is largely determined by local environmental conditions, such as climate, landscape patterns and forest characteristics, which regulate the sensitivity of ecological processes to disturbance agents (Lindenmayer et al., 2011; Seidl et al., 2016; Turner, 2010). Understanding and quantifying the vulnerability of forests and its drivers is therefore crucial in the assessment of climate risks and for the development of effective adaptation strategies. This is particularly relevant in light of the expected changes in climate that could indeed increase substantially the future risks of European forests to disturbances (Dale et al., 2001; Hanewinkel et al., 2013; Nabuurs et al., 2013; Seidl et al., 2018, 2017, 2014).

Large-scale assessment of forest vulnerability remains difficult to detect. Previous research on well-studied systems have provided important insights into the complex interactions between forest disturbances and environmental controls (Lindenmayer et al., 2011; Seidl et al., 2016; Turner, 2010). However, it is unclear to what extent the results of such local-scale analyses can be extrapolated to larger areas. Compilations of grey literature reports on past mortality events can provide large spatial coverage (Gregow et al., 2017; Schelhaas et al., 2003; Seidl et al., 2014; Senf et al., 2018). On the other hand, the coarse resolution at which data is usually recorded (e.g., country level) strongly masks the spatial variability of the phenomena.

Increasingly available satellite datasets of forest disturbances offer high spatial resolution and are globally consistent, supporting large-scale comparative efforts (Wulder and Coops, 2014). However, while the global mapping of forest disturbances is now feasible (Hansen et al., 2013; Mildrexler et al., 2009), attributing disturbance agents from remote sensing data remains challenging (McDowell et al., 2015). Recent studies have used such satellite retrievals to explore the dependence of tree mortality on environmental controls (Senf et al., 2018; Sommerfeld et al., 2018), yet without distinguishing the vegetation response to different agents of disturbances. In addition, these studies have typically considered a limited set of drivers (Neumann et al., 2017; Sommerfeld et al., 2018) and explored vulnerability relations aggregated at regional level. Such approaches typically adopt “a priory” knowledge to identify the functional relationships that links vulnerability and drivers. Therefore, possible amplification or dampening effects that may emerge at local scale from interactions amongst multiple factors or compound events (Zscheischler et al., 2018) cannot be fully disentangled.

On the modelling side, Dynamic Global Vegetation Models (DGVMs), now widely applied tools for policy relevant assessments on the impact of climate change on terrestrial ecosystems, have recently started to account for forest disturbances through equations of varying complexity (Bonan and Doney, 2018; Chen et al., 2018; Kautz et al., 2018). However, DGVMs show important limitations in reproducing the interplay between forest disturbances and environmental controls due to our incomplete understanding and model representation of such processes (Forkel et al., 2019).

Here, we investigate in a consistent framework the vulnerability of European forests to three major climate-related disturbances, including abiotic (wildfires, windstorms) and biotic (insect outbreaks) agents, over the 2000-2017 period. We used artificial intelligence methods (random forest, RF) to identify the emergent relationships between biomass loss and a comprehensive set of climate, landscape and forest metrics. These variables have been retrieved from a new spatially explicit database of forest disturbances built on the integration of multiple state-of-the-art satellite products, land surface climate datasets and human settlement layers. We applied the resulting models over the Europe domain to explore the spatial and temporal variations in vulnerability, identify their key drivers and detect possible hotspot regions.

2. Methods

This work focuses on the assessment of vulnerability of European forests to three major natural disturbances: fires, windstorms and insect outbreaks. The term vulnerability expresses here to what degree forest ecosystems are affected when exposed to a given disturbance and it is quantified in potential relative above ground biomass losses (B_L) (0% means a forest not vulnerable to the given disturbance, 100% means a forest that, when exposed to the given disturbance, is completely damaged). For each disturbance type, we developed a random forest regression model to predict the observed biomass losses (response variable) based on a set of environmental variables (predictors). Here, the environmental variables are grouped in three main categories including forest, climate and landscape. Forest features include vegetation parameters describing the average forest state and productivity, such as biomass, growing stock volume, leaf area index, tree age, tree density and tree diameter. Climate features include annual values of temperature, precipitation and snow conditions, their long-term averages, and their anomalies occurred in the years preceding the disturbance. Landscape features include population density, landscape spatial variability metrics and geomorphological parameters (e.g., elevation, slope). An extensive list of all features and corresponding descriptions is reported in Table A1.

Vulnerability models are calibrated and validated on a large set of records of forest areas affected by natural disturbances over the 2000-2017. . Fires were retrieved from the European Forest Fire Information System (EFFIS), windthrows from the European Forest Windthrow dataset (FORWIND, (Forzieri et al., 2019)) and insect outbreaks from the National Insect and Disease Survey (IDS) database of the United States Department of Agriculture (USDA). Despite the focus on Europe, for insect diseases we utilized the IDS-USDA database due to the lack of analogous monitoring systems in Europe. To increase the transferability of vulnerability models to insect outbreaks to Europe, only records where host tree species and forest pests were compatible with the European environmental conditions, were selected. Models are finally used to extrapolate in space - over the full European spatial domain - and time - over the 2000-2017 period -the annual vulnerability of forest. Based on the resulting time series, linear trends are computed to assess the temporal variations of vulnerability occurring in each grid cell of the European domain and their significance is evaluated by the Mann-Kendall test. In order to get insights about the physical processes governing the observed changes in vulnerability, spatial and temporal drivers are disentangled. To quantify the total annual vulnerability to multiple disturbances we define the Overall Vulnerability Index (OVI) under the assumption that the considered disturbances are independent and mutually non-exclusive. Similarly, to the vulnerability of single disturbance, OVI is quantified in relative potential biomass losses.

3. Results

3.1. Forest vulnerability and its key drivers

Forest vulnerability shows large differences across the spatial domain and the considered natural disturbances. Averaging over the whole domain, vulnerability to windstorms appears to be the disturbance that induces the largest biomass loss both in relative and absolute terms (~38%, ~17 t ha^{-1}) when compared to fires (~24%, ~12.5 t ha^{-1}) and insect outbreaks (~21%, ~9 t ha^{-1}). However, values aggregated at Europe level, largely mask the substantial spatial variations in vulnerability. Strong geographical gradients emerge showing generally higher vulnerability values in northern and Mediterranean countries (Fig. 1a,c,e). In particular, forest vulnerability to windstorms show higher values in north-western Scandinavian Peninsula, northern British Islands, Iberian Peninsula and Turkey.

Vulnerability to fires is higher in northern Scandinavia, Iberian Peninsula and Turkey, whereas vulnerability to insect outbreaks shows higher values in north-eastern Scandinavian Peninsula and European Russia. Central Europe shows generally lower vulnerability values consistently across the various disturbances. Forest characteristics largely determine the vulnerability to fires and windstorms showing a larger marginal contributions compared to climate and landscape drivers over most of Europe (Fig. 1b,d). For these disturbances, landscape features (e.g., landscape spatial variability) exert a main influence in some localized areas such as in the Balkan countries and inland European Russia.

Climate affects prominently the vulnerability to insect outbreaks in large part of Europe except in the Italian peninsula, north-western Iberian Peninsula, Balkan countries, central Europe and north-western Scandinavian Peninsula, where also forest development factors appear important (Fig. 1f). **Overall, results show the key role of forest features in determining the vulnerability of European forests to natural disturbances.**

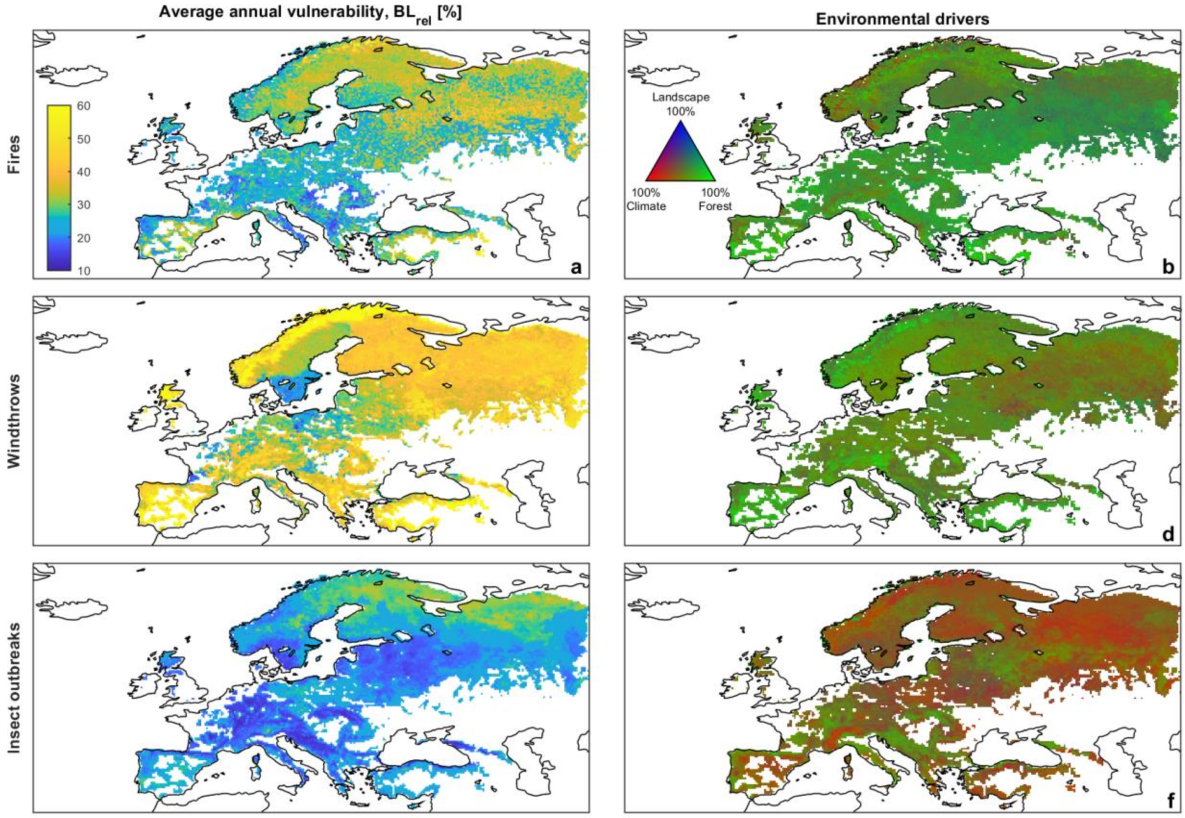

Figure 1. Spatial maps of vulnerability of European forests to natural disturbances and marginal contribution of key factors. (a) Average annual vulnerability of European forests to fires. (b) Marginal contribution of forest features, climate and landscape factors (categories shown in Table A2.1) to the vulnerability to fires. (c,d) and (e,f) as (a,b) but for windstorms and insect outbreaks, respectively.

3.2. Emergent trends in forest vulnerability

At Europe level the vulnerability of forest in the last two decades is on average almost unchanged ($4{\cdot}10^{-4}$, $3.8{\cdot}10^{-3}$ t ha^{-1} $year^{-1}$, wood tonnes per hectare per year) for fires, windstorms and substantially increasing (0.55 t ha^{-1} $year^{-1}$) for insect outbreaks. However, the continental average is masking the large contrasting trends emerging at local scale over the study area (Fig. 2a,c,e). This is evident for the trends in vulnerability to fires where many areas, such as the Italian peninsula, Greece and Central Europe show prominent decreasing trends in vulnerability, in contrast with the general tendency in the rest of Europe (Fig. 2a), possibly driven by a reduction in available fuel (vegetation productivity). Higher increase in vulnerability to fires appear in Portugal and in the Carpathians Mountains. Large spatial variability in trends emerges for the vulnerability to windstorms. Larger positive increase in vulnerability is found in Central European Russia, Northern Scandinavian Peninsula, South of France, Central Italy, Balkan countries and Carpathian Mountains (Fig. 2c). Trends of opposite sign appear mostly in Northern European Russia, Eastern Scandinavian Peninsula, Central and Eastern Europe.

Among the three natural disturbances under evaluation, the vulnerability to insect outbreaks shows a clear average increase over the entire domain prominently in European Russia, Scandinavian Peninsula, central and eastern Europe (Fig. 2e). Decreases in vulnerability are found along the Urals Mountains, Baltic countries, British Islands and to some extents part of the Scandinavian and Iberian Peninsula.

While recognizing that the observational period is relatively short for trend analysis, we point out that spatially consistent patterns of trends emerge across Europe for all three disturbances considered, as described above. Furthermore, the emerging changes are significant (p-values<0.05, Mann-Kendall test) almost everywhere for insect outbreaks, and prominently in northern Europe for fires and windstorms. It is worth noting that in the recent two decades insect outbreaks, and in particular bark beetles, have been responsible for massive and destructive attacks on coniferous forests of North America. Similar events are currently occurring in eastern European countries like Poland and Slovakia.

Changes in climate drivers occurred over the last two decades and are largely responsible for the observed variations in vulnerability. In fact, the combination of **increases in temperature over the whole region, and decreases in precipitation particularly in north-western Europe have contributed substantially to make European forests more vulnerable to natural disturbances** (Fig. 2b,d,f).

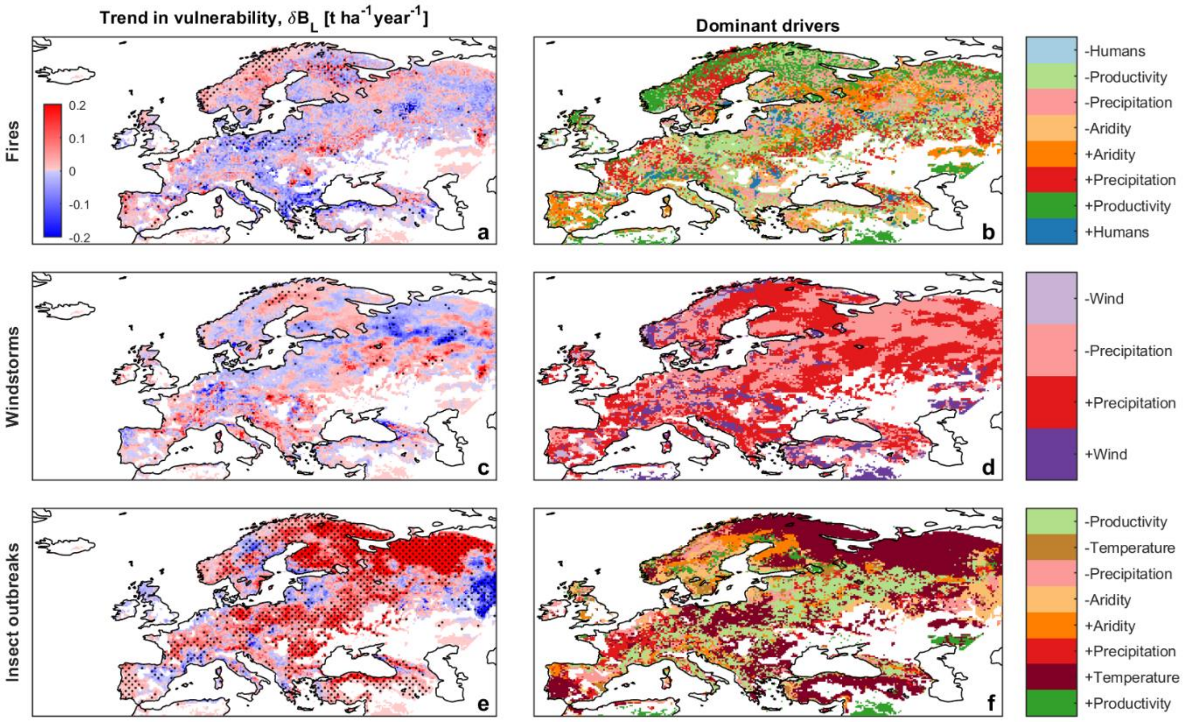

Figure 2. Spatial maps of the temporal trends in vulnerability and its dominant drivers. (a) Temporal trend in vulnerability of European forest to fires. Black dots show pixels where trends are significant (Mann-Kendall test; p-value<0.05). (b) Dominant drivers of the trends observed in (a) and grouped in sub-categories shown in Table A2.1. (c,d) and (e,f) as (a,b) but for windstorms and insect outbreaks, respectively.

3.3. Spatial and temporal patterns of overall vulnerability index

When multiple disturbances are integrated into the overall vulnerability index (OVI), results show that European forests have a vulnerability of ~62% (corresponding to ~28 tons of above ground biomass per hectare), averaged over the whole study domain, meaning that a forest exposed to the combination of natural disturbances on average shows a reduction of biomass of about 62%. Areas with higher vulnerability values to multiple disturbances appear in the northern European Russia, Iberian Peninsula, northern Scandinavian Peninsula, British Islands and Turkey (Fig. 3a). Spatial patterns are largely driven by the vulnerability of forests to windstorms, which is the dominant contributor to the OVI (Fig. 1c). At Europe level, the OVI experienced an increase of 0.26 t ha^{-1} $year^{-1}$ over the observational period with larger values in northern European Russia, Scandinavian Peninsula, eastern Europe and Balkan countries, following mostly the patterns in the trends of vulnerability to insect outbreaks (Fig. 3b and Fig. 2e). **Results show that large parts of the European forests are substantially vulnerable to at least one natural disturbance and that many of the areas more vulnerable have experienced a higher increase in vulnerability over the last two decades due to changes in climate.**

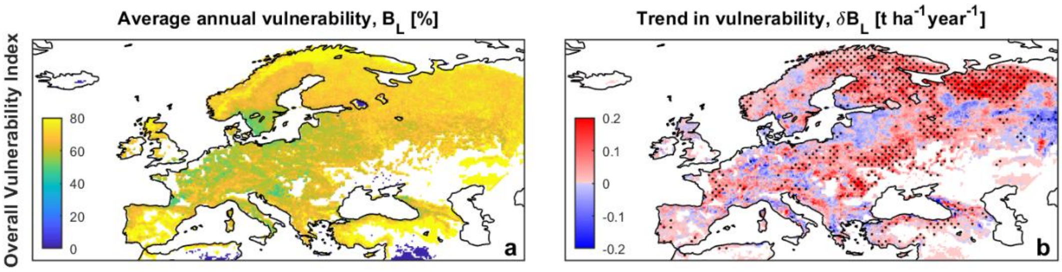

Figure 3. Spatial and temporal patterns of the overall vulnerability index. (a) Annual average vulnerability of European forest to multiple disturbances. (b) Temporal trend in vulnerability of European forest to multiple disturbances. Black dots show pixels where trends are significant (Mann-Kendall test; p-value<0.05).

4. Conclusions and future research directions

In this study, we explored and quantified for the first time the vulnerability of European forests to three major natural disturbances, including fires, windstorms and insect outbreaks. We use a data-driven framework, which allowed a full characterization of the key drivers of vulnerability in a spatially explicit manner and disentangle their effects. Spatial and temporal variations in vulnerability are analysed in order to identify potential hotspots with increased susceptibility to natural disturbances. Overall, the analysis of vulnerability detailed here represents a key first step for estimating present and future risks of European forest to natural disturbances.

In this regard, ongoing and future research aim to explore the following key aspects:

- Quantification of the hazard component for each natural disturbance over the historical period. The approach focuses on the use of a Random Forest Classification model to quantify, in a data-driven framework, the probability of occurrence of each natural disturbance.
- Quantification of the exposure component in terms of carbon storage, economic value of forest and biodiversity. The method focuses on the data integration of satellite high-resolution forest cover changes with the static biomass maps. Additional information on economic value of forests will be also accounted, based on the current tree species distributions and the actual wood market.
- Quantification of the present climate risks of European forest to natural disturbances. The approach is based on the integration of the vulnerability (presented here), exposure and hazard components and will provide an estimate of carbon storage and economic value of forest at risk due to natural disturbances.
- Quantification of future risks of European forest to natural disturbances. The approach will focus on the integration of vulnerability, hazard and exposure components under future climate and forest management conditions.

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Annexes

Annex 1. Methodology

A1.1. Forest disturbances and plant functional types

We focus on the vulnerability of European forests to three major natural disturbances, including forest fires, windstorms and insect outbreaks (bark beetles, defoliators and sucking insects). In order to calibrate/validate vulnerability models we used forest areas affected by disturbances over the 2000-2017 period and retrieved from the European Forest Fire Information System (EFFIS), the European Forest Windthrow dataset (FORWIND, Forzieri et al., *in review*) and the National Insect and Disease Survey (IDS) database of the United States Department of Agriculture.

We explored the vulnerability of plant functional types (PFTs) as derived from the land cover map of the European Space Agency Climate Change Initiative (ESA-CCI) including broadleaved deciduous (BrDe), broadleaved evergreen (BrEv), needle leaf deciduous (NeDe) and needle leaf evergreen (NeEv).

A1.2. Biomass loss and environmental variables

In this study the term vulnerability expresses the relative interannual variation in biomass (ΔB) when exposed to a given disturbance. First, the temporal variations in biomass over the 2000-2017 period were reconstructed from the integration of satellite high-resolution forest cover changes with the static biomass map available for year 2010 (Ceccherini et al., *in preparation*). Then, for each disturbed forest area at year *t* the corresponding relative biomass loss ($B_{L,t}$) was quantified based on the difference of pre- and post-disturbance biomass, as follows:

$$B_{L,t} = \left[\frac{max(B_{t-n},\ldots,B_t) - min(B_t,\ldots,B_{t+m})}{max(B_{t-n},\ldots,B_t)}\right], \qquad (1)$$

where *n* and *m* represent the backword and forward temporal lags (in years), respectively, and express the temporal window over which a biomass loss can be reasonably attributed to a given disturbance. For fires and windstorms, *n* and *m* have been set both to 1, as these disturbances typically lead to an abrupt loss in vegetation. For insect outbreaks, *n* and *m* have been set to 2 and 5, respectively, in order to capture the progressive and slow change in biomass following an insect infestation.

Estimates of ΔB_t are complemented with a comprehensive set of environmental variables reflecting the forest (F), climatic (C) and landscape (L) conditions and collected from multiple sources in a single harmonized database (Girardello et al., *in preparation*). Forest features include vegetation parameters describing the forest state and productivity, such as biomass, growing stock volume, leaf area index, tree age, tree density and tree diameter. Climate features include annual values of temperature, precipitation and snow conditions, their long-term averages, and their anomalies occurred in the years preceding the disturbance. Landscape features include population density, spatial variability metrics and geomorphological parameters. The observational datasets encompass large gradients of environmental conditions and are representative samples of the European forests, climates and landscapes.

A1.3. Vulnerability modelling

For each disturbance type, we developed a random forest regression model to predict the observed biomass losses (response variable) based on a set of environmental variables (predictors). In order to reduce the effects of the potential spatial dependence in the observational datasets we preliminarily resampled B_L, F, C and L along the gradients of the three principal components derived from the set of predictors. Furthermore, to reduce potential redundancy in the predictors set, we implemented a feature selection procedure, which enabled us to identify an optimal subset of F, C and L predictors (Q hereafter for short). The list of the selected variable is reported in Table A2.1. The resulting formulation is as follows:

$$B_L = v(Q), \qquad (2)$$

where *v* is the vulnerability model. Vulnerability models were further refined by retrieving *v* functions for each single PFT. Random forest models were calibrated using 60% of records randomly selected for each year form the entire dataset, while the remaining 40% of records was used for the validation. Average model performances expressed in terms of R^2 range between 0.38 and 0.53 across the three disturbances considered with higher goodness of fit for windstorms. Furthermore, the emerging relationships between response variable and each predictor were visually inspected by partial dependence plots. The emerging patterns are largely reasonable and consistent with the underlying physical processes and corroborate the chosen modelling approach.

A1.4. Spatial and temporal patterns of vulnerability

PFT-specific vulnerability models were used to predict the vulnerability for each year of the observational period and for each grid cell (0.25 degree) of the spatial domain. The models assumes that the sampling of response variables and predictors is representative for the whole region. Such estimates were then averaged at grid cell level based on the cover fractions of PFTs. This results in a time series of spatial maps of annual vulnerability to each natural disturbance. Spatial and temporal variations in vulnerability are both expressed in relative and absolute terms. The latter one is retrieved by rescaling estimates of relative biomass loss based on the available biomass.

Spatial dependence of vulnerability on each predictor was retrieved from the slope of the Individual Conditional Expectation (ICE) calculated in each grid cell. The marginal contributions Z of forest (F), climatic (C) and landscape (L) variables, hereafter referred as X for short, are then derived as follows:

$$Z_X = \frac{\sum_{i \in X} |\alpha_i|}{\sum_{j \in Q} |\alpha_j|}, \qquad (3)$$

where α represents the slope of ICE, *i* runs over all predictors of *X* whereas *j* runs over all available predictors. Long-term linear trends in vulnerability were quantified for each grid cell and their significance evaluated by Mann-Kendall test. In order to isolate the drivers of temporal variations in vulnerability a set of factorial simulations were performed. To this aim, we estimated for each year and for each grid cell of the spatial domain the relative biomass loss due the temporal variation in a given k predictor (ΔB^k), as follows:

$$B_L^k = v(Q) - v^k(Q), \qquad (4)$$

Where $v(Q)$ reproduces the biomass loss when all variables are dynamic, while $v^k(Q)$ reproduces the biomass loss when all variables are dynamic except the *k* predictor. Long-term linear trends in vulnerability associated to each *k* dynamic predictors were computed in order to identify the key determinant of the emerging trends in vulnerability.

A1.5. Overall vulnerability index

To quantify the total annual vulnerability to multiple disturbances we defined the overall vulnerability Index (OVI), similarly to the multi-hazard index developed in ref.(Forzieri et al., 2016). Under the assumption that the considered disturbances are independent and mutually non-exclusive, from the inclusion-exclusion principle of combinatorics the OVI can be expressed as follows:

$$OVI = \bigcup_{p=1}^{D} B_{L,p} = \sum_{q=1}^{D} \left((-1)^{q-1} \cdot \sum_{\substack{I \subset \{1,\ldots,D\} \\ |I| = q}} B_{L,I} \right), \qquad (5)$$

where *p* refers to the disturbance-specific B_L, D is the number of disturbances considered, the last sum runs over all subsets *I* of the indices {*1,…,D*} containing exactly *q* elements, and

$$B_{L,I} := \bigcap_{p \in I} B_{L,p}, \qquad (6)$$

expresses the intersection of all those $B_{L,p}$ with index in *I*.

Annex 2. Extended results

Table A2.1. List of selected predictors in the vulnerability models. Long-term metrics refer to the 1982-2017 period, while short-term metrics refer to the 6 years preceding the disturbance.

Category	**Sub-category**	**Variables**		**Fires**	**Windstorms**	**Insect outbreaks**
		Name	**Spatial resolution**			
Forest development	Productivity	Biomass	100 m	X	X	X
		Growing stock volume	100 m	X	X	X
		Leaf area index	250 m	X		X
		Tree age	0.25 degree	X	X	X
		Tree density	1 km	X	X	X
		Tree height	1 km		X	X
		Tree diameter	1 km		X	
		Basal area	1 km			X
Climate	Temperature	Long-term average temperature	4 km		X	X
		Short-term anomaly in maximum temperature	4 km			X
		Short-term anomaly in average temperature	4 km			X
	Precipitation	Long-term average precipitation	4 km			X
		Annual average precipitation	4 km	X	X	
		Annual cumulated snow	4 km		X	
		Short-term anomaly in average precipitation	4 km			X
		Short-term anomaly in minimum precipitation	4 km			X
	Aridity	Standardized Precipitation Evapotranspiration Index	4 km			X
		Aridity index	4 km	X		
		Fire weather index	0.25 degree	X		
	Wind	Annual maximum wind	0.5 degree		X	
Landscape	Humans	Population density	0.25 degree	X		
		Homogeneity Enhanced Vegetation Index	1 km	X	X	
		Evenness Enhanced Vegetation Index	1 km		X	
	Geomorphology	Altitude	1 km		X	X
		Slope	1 km		X	

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