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RESEARCH ARTICLE

Significant increase in natural disturbance impacts on European forests since 1950

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Abstract

Over the last decades, the natural disturbance is increasingly putting pressure on European forests. Shifts in disturbance regimes may compromise forest functioning

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and the continuous provisioning of ecosystem services to society, including their climate change mitigation potential. Although forests are central to many European policies, we lack the long-term empirical data needed for thoroughly understanding disturbance dynamics, modeling them, and developing adaptive management strategies. Here, we present a unique database of >170,000 records of ground-based natural disturbance observations in European forests from 1950 to 2019. Reported data confirm a significant increase in forest disturbance in 34 European countries, causing on an average of 43.8 million m^3 of disturbed timber volume per year over the 70-year study period. This value is likely a conservative estimate due to under-reporting, especially of small-scale disturbances. We used machine learning techniques for assessing the magnitude of unreported disturbances, which are estimated to be between 8.6 and 18.3 million m^3/year. In the last 20 years, disturbances on average accounted for 16% of the mean annual harvest in Europe. Wind was the most important disturbance agent over the study period (46% of total damage), followed by fire (24%) and bark beetles (17%). Bark beetle disturbance doubled its share of the total damage in the last 20 years. Forest disturbances can profoundly impact ecosystem services (e.g., climate change mitigation), affect regional forest resource provisioning and consequently disrupt long-term management planning objectives and timber markets. We conclude that adaptation to changing disturbance regimes must be placed at the core of the European forest management and policy debate. Furthermore, a coherent and homogeneous monitoring system of natural disturbances is urgently needed in Europe, to better observe and respond to the ongoing changes in forest disturbance regimes.

KEYWORDS
bark beetles, climate change, empirical disturbance data, European forests, fire, forest natural disturbances, windstorms

1 | INTRODUCTION

European forests span over 200 million ha, covering more than one third of the continent (State of European Forest, 2020). Providing a multitude of ecosystem services to society, these forests have always been intimately linked to and influenced by European societies (State of European Forest, 2015). There is growing evidence that the results of past forest management (e.g., planted conifer monocultures, increasing growing stock [GS]) as well as the effects of climate change are accelerating the magnitude of forest disturbance impacts in Europe (Schelhaas et al., 2003; Seidl et al., 2014, p. 201; Senf & Seidl, 2021a, 2021c; Sommerfeld et al., 2018).

Natural disturbances are important drivers of forest ecosystem dynamics (Turner, 2010). Disturbance events abruptly modify the demography of forests (Mouillot et al., 2013) by killing trees, altering the functioning of the ecosystem, and affecting resource availability and the abiotic environment (Seidl et al., 2017). Canopy openings prompt tree regeneration (Franklin et al., 2002) and species diversity (Swanson et al., 2011), while dead trees contribute to nutrient recycling and biogeochemical cycles (Mayer et al., 2017), and harbor a multitude of habitats, fostering biodiversity (Lindenmayer & Noss, 2006).

The intensification of disturbance regimes reported in the last decades for Europe (Hlásny, Zimová, et al., 2021; Senf & Seidl, 2021b) is raising concerns about disturbances disrupting the continuous and sustainable provisioning of ecosystem services to society (Lindner et al., 2010; Thom & Seidl, 2016). High rates of tree mortality decrease the carbon residence time in living biomass and soils, reducing the carbon storage potential of forests (Pugh et al., 2019; Weng et al., 2012), and thus their climate change mitigation effect (Nabuurs et al., 2013; Seidl et al., 2014). The speed of global change, including its effects on disturbance frequency and extent (Seidl et al., 2017), is creating an increasingly uncertain future for forest management, making long-term forest planning increasingly difficult (Messier et al., 2019).

Considering the rapid changes in forest disturbance regimes, data regarding disturbance are crucial to understand and model disturbance dynamics, predict future ecological pathways of forest development, and assess alternative management strategies to increase forest resilience. In recent years, large progress has been made in studying disturbance using remote sensing (RS) (Chirici et al., 2020; Forzieri et al., 2021; Francini et al., 2022; Senf & Seidl, 2021b, 2021c). However, the attribution of remotely sensed canopy openings to individual causes of disturbance remains difficult (e.g., Palahí et al., 2021; Sebald et al., 2021). Furthermore, there is a lack of homogeneous, quantitative, ground-collected data, which are necessary to calibrate, validate, and complement satellite-based analyses (Senf et al., 2018).

Although individual countries collect data on forest disturbance, such as salvage logging statistics, this information is not compiled at the European level. Moreover, numerous case studies across Europe exist that studied single-disturbance events (Chirici et al., 2019; Nagel et al., 2017). However, this information remains scattered, unharmonized, and poorly accessible. Schelhaas et al. (2003) produced the Database of Forest Disturbances in Europe (DFDE), which has been widely used as a reference for pan-European information on forest disturbance from 1950 to 2000. However, the DFDE has not been updated for 20 years, resulting in a lack of consistent and curated ground-based information on natural disturbance in Europe's forests. The current study aims to fill this gap by updating the DFDE with newly available forest disturbance data from 1950 up to 2019. Specifically, the aims of this study were to:

1. Provide an up-to-date overview of trends in forest disturbance impacts in Europe over the last 70 years and quantify their geographical and temporal changes;
2. Assess the completeness of empirical disturbance observation and its implications for the analysis of trends;
3. Discuss the relevance of natural disturbances on European forest resources.

2 | MATERIALS AND METHODS

2.1 | Updating the database of forest disturbances in Europe

To gather natural disturbance data, we carried out a literature review with two main foci: (i) filling the gaps in the time-series presented in the first version of the DFDE, particularly for countries that were not included in the database previously and (ii) extending the data from 2000 to 2019. The review was structured in two blocks. One consisted of a classical literature screening using *Google Scholar* to search for a set of keywords (*forest natural disturbance in Europe*, *forest windstorm damage*, *forest pest outbreaks*, *forest damage*, *forest wild-fires in Europe*), complemented by specific web searches for time-series reported by national forest inventories, national statistical offices and specialized databases (Gardiner et al., 2010; San-Miguel-Ayanz et al., 2013). The other block consisted of mobilizing a network of experts across Europe and asking them for archive literature research. This approach was deemed helpful as in many countries of Europe, a lot of information exists in old archives, recorded in paper form and presented in local languages, which is not easily accessible by the international scientific community. We defined "*forest disturbance*" as a natural event which causes the abrupt loss of live tree biomass, damaging the GS, and affecting the demographic structure of the forest. All potential sources found were screened for data that complied with our definition of forest disturbance, contained a disturbance cause, a geographic location (usually a name of a region or country) and a quantitative or qualitative description of the damage caused. Data were added to the DFDE, using as much as possible the original terminology and keeping relevant additional information such as the exact dates. The updated version of the DFDE is presented with a new interface (see Patacca et al., 2021) and is now publicly available online at https://dfde.efi.int/db/dfde_app.php (Schelhaas et al., 2020). The data contain information on disturbance expressed in timber volume, area, percentages or number of disturbance events separated by disturbance agent. The spatial scale varies with the source, ranging from event-based studies to country statistics.

2.2 | Construction of national time-series

In the first step toward constructing national time-series, we retrieved from the DFDE all records that contained reported timber volume or area disturbed, and were reported at the national or subnational level for the countries included. Causes of disturbance were allocated to one of the following five agents: wind (including cyclonic storms, thunderstorms, and tornadoes), fire, European spruce bark beetle (*Ips typographus*, L. feeding on *Picea abies*, L., H. Karst), other biotic agents (i.e., fungi, nematodes, other insects, pathogens, and animals damaging trees) and other abiotic disturbance (i.e., drought, snow, ice, hail, and rime). Records mentioning *bark beetles* without a specific insect species or tree species affected were allocated to the agent European spruce bark beetles. We note that there are other species of bark beetles that feed on different host tree species throughout Europe but based on available data in the DFDE other bark beetle species are contributing less than 5% to the total disturbance caused by bark beetles in Europe. Separating European spruce bark beetles (hereafter referred to as bark beetles) from bark beetles affecting other species was needed for the gap-filling described later. For fire, we selected records explicitly referring to burned forested land.

In the second step, we cleaned the data to arrive at a single reported value for each year, each country, and each disturbance agent. This included a process to determine which source to include in the time-series, followed by a check to remove duplicate data points (e.g., where a report from an individual region was also included in a nationally reported summary). We always prioritized peer-reviewed and/or official sources such as scientific papers, international or country reports over other sources. In cases where several values were reported for the same disturbance event we selected the value from the most consistent source in terms of continuity and applied method. This means that we gave preference to longer time-series of the same methodology to ensure consistency in the analysis across years. In case of equal length of time-series, we preferred the source with the best documentation of reporting methodology. When specified, timber volume under bark was converted to volume over bark following Schelhaas et al. (2003). When a literature source reported the total amount of damage over a period of multiple years and no auxiliary information was available, we averaged the amount over the time period (1.65% of the data). Fires are commonly reported in terms of burned forest area, while all the other disturbances were reported in cubic meters of damaged timber. To enable a comparison across agents, we converted forest area burned into fire-damaged timber volume using a country-specific Fire-damage Conversion Factor (FCF). We retrieved all available studies from the DFDE where the timber volume damaged by fire per hectare (m^3/ha) was reported. Where multiple studies per country were available, we averaged them to obtain a country-level FCF. In case no FCF was available for a country, it was derived by averaging over FCFs from countries of the same ecological zone (see below). For all other countries a FCF of 25 m^3/ha was assumed following Schelhaas et al. (2003). Finally, timber volume damaged by fire per year was computed by applying Equation (1):

$$FD_i^y = \left(A_i \times FCF_i\right) \qquad (1)$$

where FD_i^y is the total fire damage of country i in year y, A_i is the burned forest area (ha) of country i and FCF_i is the FCF of country i. Of the 34 countries included in this study, 12 countries had a country-specific FCF. Fourteen countries had an FCF derived from countries of the same ecozone, while eight countries were assigned the default FCF of 25 m^3/ha. The FCF of each country is reported in the supplementary materials 1. For modeling purposes we grouped the countries in ecological zones (ecozones) following Schelhaas et al. (2003) (Figure 1). Since the geographical area of the DFDE analysis was extended, we included the Baltic states (Latvia, Lithuania, and Estonia) in the Northern ecozone, hereafter called "Northern/Baltic." Altogether, we studied 34 countries in Europe, grouped in eight ecozones and representing 201.8×10^6 ha of forest land (State of European Forest, 2020).

2.3 | Expert's interpretations of reported time-series

We expected that a complete time-series for a country for a specific disturbance agent would consist of one reported value for every year, including years with zero damage, years with low to intermediate severity damage (hereafter referred to as *chronic damage*, Kosiba et al., 2018), and years with larger events. However, some countries reported only the very big, catastrophic events (e.g., individual windstorms or pest outbreaks), but not chronic disturbances (damage patterns ranging from scattered gaps to moderate sized canopy openings caused by, e.g., thunderstorms or endemic bark beetle populations). This resulted in many time-series with a few big peaks and no chronic disturbance damage in between, which led us to suspect that the reporting was incomplete. In some cases, however, time-series had only a few gaps over a more or less complete series of reported disturbances for a certain agent, which may be caused by true zeros in the data. To distinguish between true zeros and non-reported chronic damage, we consulted experts to assess if zeros represented a gap in the data or if no disturbance occurred in these years. Based on these consultations we labeled time-series as complete, incomplete (when records were interspersed with gaps) or empty (when no data at all were reported). If country experts confirmed that none or (most probably) very little disturbance happened in a certain year with no reporting, then the time-series was considered complete and gaps were explicitly set to zero. Otherwise, the time-series was labeled incomplete or empty, for which gap-filling was applied if possible (see below). This exercise resulted in two sets of time-series: (i) one consisting solely of reported data and the second (ii) of zero-filled time-series based on expert interpretation (supplementary materials 2).

2.4 | Time-series gap-filling

To fill the identified gaps in the data and predict the level of disturbance in years with missing data, we used a machine learning approach, applying the supervised ensemble regression algorithm Random Forest (RF) (Breiman, 2001; *randomForest* R package Version 4.7-1, 2022). RF is a powerful tool for regression predictions (Ließ et al., 2012; Segal, 2003), particularly suited for situations that include complex interactions between variables (Seidl et al., 2011; Strobl et al., 2007), like disturbance. We built a set of 42 predictor variables for explaining disturbance occurrence (Seidl et al., 2011). Those predictors included 8 forest variables and 34 environmental variables aggregated at the country scale. The forest variables included GS, forest area, standing GS of conifer species, area and GS of *P. abies*, all derived from a Joint Pan-European data set (FOREST EUROPE, UNECE, FAO, 2020, https://fra-data.fao.org/FE/panEuropean/home/). We retrieved age-class distributions for the period 1950 to 2010 from (Vilén et al., 2012). The age class data from 2011 to 2019 and the years between reportings of all the other forest variables were imputed applying multiple-chained equations, using the *mice* R package (Van Buuren & Groothuis-Oudshoorn, 2011). From the age class time-series, we derived the average forest age, share of old forest (>120 years), and skewness of age class distribution as predictors used in gap-filling. Climate variables were derived from the ERA5 reanalysis data set, available online at the Copernicus Climate Data Store (CDS, https://cds.climate.copernicus.eu/). The raster-stacked file was clipped by the country's borders using official NUTS0-2021 EU data (European Commission—Eurostat/GISCO, 2021). The calculations were performed in the CDS Toolbox Editor online environment. Climate variables included daily average temperature and cumulative precipitation, both aggregated annually, by trimesters and lagged by 1 year to account for the lagged effect of droughts (Seidl et al., 2011). Maximum wind speed (maxWS) was both selected from daily and from monthly averaged values. MaxWS was aggregated yearly and by trimester. Moreover, we calculated an extra variable called wind weight index (WWI, Equation 2):

$$WWId_i = \left(Pd_i \times maxWSd_i\right) \qquad (2)$$

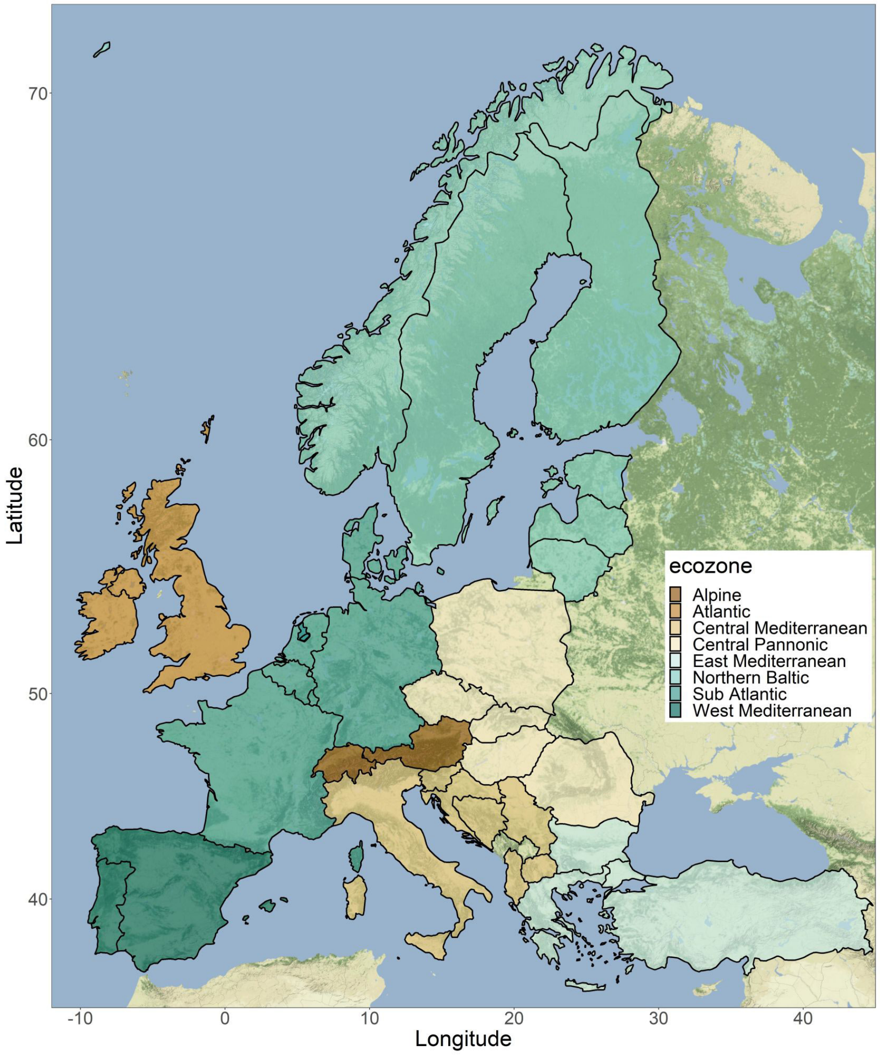

FIGURE 1 Division of the countries included in this study in ecological zones (ecozones). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

where $WWId_i$ is the wind weight index (kg/ms), Pd_i the precipitation (mm) and $maxWSd_i$ the maxWS (ms^{-1}) of day i. We developed this index to represent the interaction effect between wind and precipitation during storms. Precipitation during a windstorm event adds extra weight to the canopy, increasing the bending forces onto the stem when the stem is displaced by the wind (Gardiner et al., 2008). The maximum daily WWId per trimester was used as a predictor variable. A list of all variables used for gap-filling is available in supplementary materials 3.

We trained a series of RF models for each disturbance agent (5) and ecozone (8), allowing the algorithm to identify specific ecological relationships for the different ecozones. The RF models were separately trained on both reported only and expert's interpreted time-series, (respectively, left-hand- and right-hand flow in Figure 2) using the log-transformed yearly disturbance damage (m^3/year) per country and disturbance agent as response variable. We log-transformed the response variable to address the skewness of the data. This resulted in two groups of RF models for gap-filling (40 models in each group, 5×8), (i) one trained on reported data only (left-hand circle in Figure 2) and (ii) one trained on zero-filled data after expert's interpretations (right-hand circle in Figure 2). We selected the models with the lowest root-mean square error (RMSE) and used these models to make predictions on the full time-series (Figure 2 shows a workflow diagram of the modeling exercise). When a disturbance agent had no records in an entire ecozone we assumed the relevance of this agent was negligible in that ecozone (e.g., snow damage in the Eastern Mediterranean). Bark beetle predictions were applied only for countries with Norway spruce area >0. After running the gap-filling models, the predicted values were back-transformed to obtain a gap-filled time-series of disturbed timber volume (m^3/year). Finally, the predicted values of disturbed timber volume were used to fill the empty years of the two groups of time-series.

2.5 | Trend analysis of gap-filled data

We analysed each combination of disturbance agent and ecozone of the gap-filled time-series based on expert interpretation for temporal trends using a Mann–Kendall trend test. Mann–Kendall is a non-parametric test (Kendall, 1975; Mann, 1945) used to determine the significance of a trend in a time-series. We used a non-parametric test, since our data do not comply with the assumptions of normality.

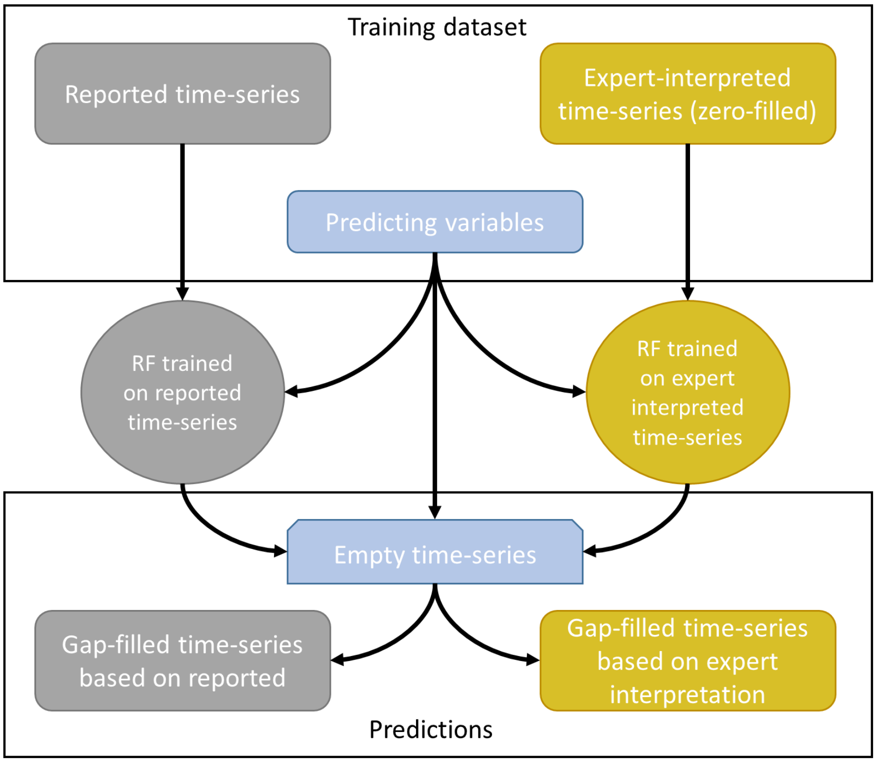

FIGURE 2 Conceptual flow diagram of the gap-filling exercise.

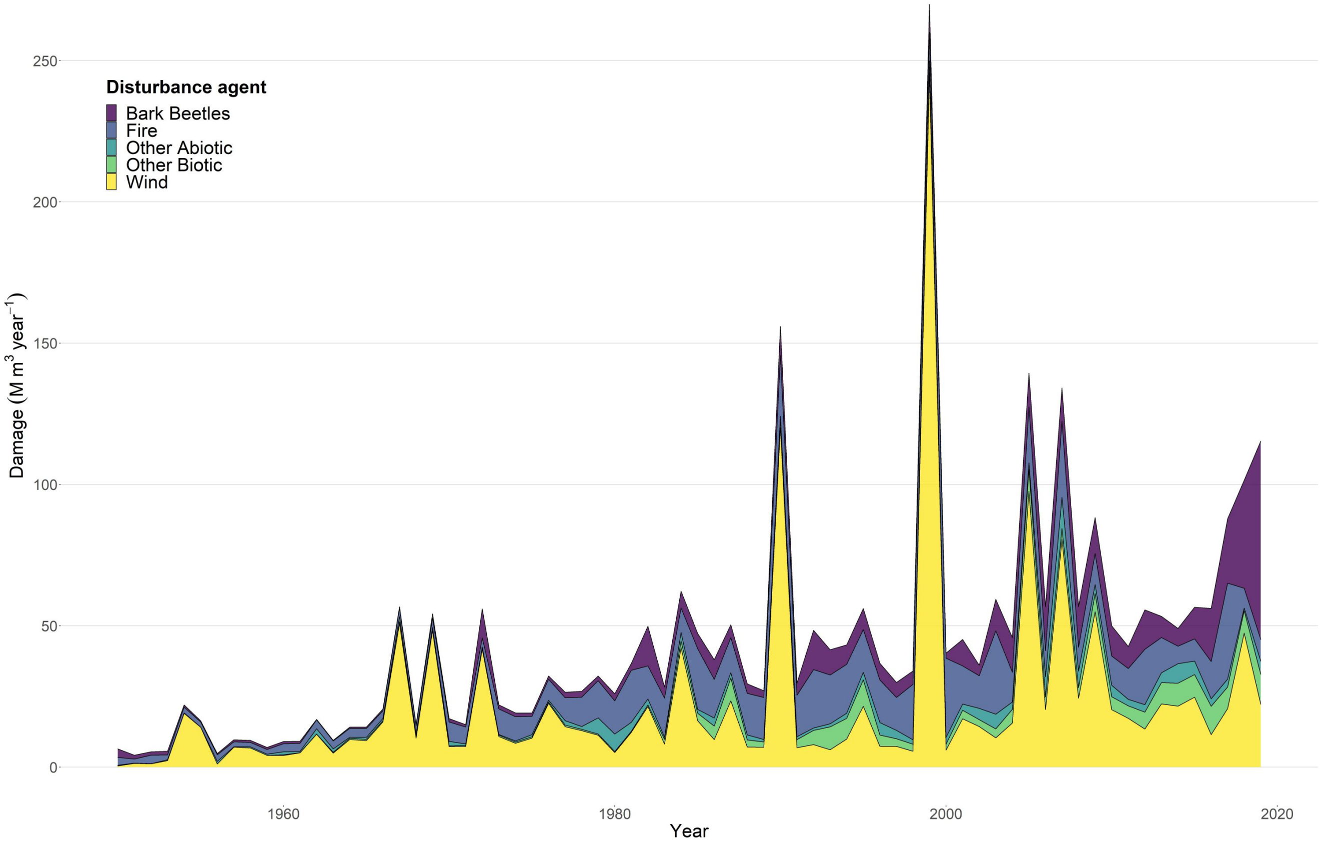

FIGURE 3 Total reported damage caused by natural disturbance in Europe between 1950 and 2019.

Moreover, the test can tolerate outliers well (Hamed & Rao, 1998). The Mann–Kendall test is widely used to detect trends in climatic or hydrologic time-series (Hamed & Rao, 1998) but is also used to analyse fire regimes (e.g., Jiménez-Ruano et al., 2017; Salguero et al., 2020). The *tau* parameter of the test ranges from −1 to +1 and indicates if the trend is negative or positive, with larger values

TABLE 1 Variance explained (%) by the two sets of random forest models (trained on reported and expert's interpreted timeseries, respectively) for each combination of ecozone × disturbance agent

	Disturbance causes									
	Wind		Fire		Bark beetles		Other biotic		Other abiotic	
Ecozone	Reported	Experts interpreted	Reported	Experts interpreted	Reported	Experts interpreted	Reported	Experts interpreted	Reported	Experts interpreted
Alpine	39.06 (1.18)	60.51 (3.99)	39.14 (1.02)	39.47 (1.03)	78.73 (0.80)	78.15 (0.81)	~	~	8.17 (1.12)	6.42 (1.04)
Atlantic	21.52 (1.85)	~	~	~	~	~	NA	NA	NA	NA
Central Med.	33.7 (1.00)	29.75 (3.14)	88.84 (0.95)	90.2 (0.95)	83.15 (0.68)	77.4 (2.77)	87.68 (0.86)	83.56 (2.16)	64.18 (1.26)	16.26 (3.24)
Central Pannonic	54.57 (0.67)	74.64 (3.07)	69.69 (0.79)	43.4 (1.27)	85.1 (0.49)	62.02 (2.79)	84.51 (0.49)	89.76 (0.55)	44.22 (0.91)	45.05 (3.48)
East Med.	~	5.02 (4.25)	68.95 (1.01)	68.43 (0.98)	NA	NA	NA	NA	NA	NA
Northern Baltic	24.59 (1.63)	7.01 (4.11)	46.58 (1.07)	43.04 (1.25)	44.43 (1.11)	43.52 (1.20)	26.44 (1.37)	29.55 (1.29)	78.8 (0.86)	79.75 (0.44)
Sub-Atlantic	9.64 (2.75)	35.34 (5.32)	90.3 (0.90)	90.4 (0.90)	23.37 (1.97)	55.08 (4.35)	72.16 (1.54)	81.23 (1.98)	18.04 (1.62)	42.06 (4.26)
West Med.	~	~	70.93 (0.57)	71.87 (0.57)	NA	NA	NA	NA	NA	NA

Note: NA indicates that there was no data to train a RF model. The ~ symbol indicates that no RF model was fitted for this combination due to limited data availability. The values in the brackets are the root mean squared error (RSME).

reflecting stronger trends. We used a significance level (p-value) of $\alpha = .05$ (Kendall, 1975; Mann, 1945). The tests were performed using the *Kendall* R package (Hipel & McLeod, 1994; Version 2.2.1, 2022). To further assess trends, we analysed time-series applying the non-parametric Sen's slope estimator test (Sen, 1968). Sen's slope test provides an estimate for the magnitude of a trend. It can be interpreted as the average change of yearly damage across the whole time-series. This analysis was performed using the *trend* R package (version 1.1.4, 2020).

2.6 | Disturbance impact on forest resources

In addition to GS, we retrieved harvest data for each country, available from 1961 to 2019 in the FAO database FAOSTAT (Food and Agriculture Organization of the United Nations, 1997), to derive the relative impact (%) of the total damage caused by disturbance on GS and harvest. We assessed the impact for two periods, as well as across the overall time-series. Finally, we weighted the disturbance damage for each country and year by the country's forest area (ha) of that year, obtaining a Standardized Disturbance Index (SDI) expressed in m^3/ha/year for each country. We averaged these values by decade and over the whole study period, and compared the temporal changes in SDI across countries.

3 | RESULTS

3.1 | The updated database of forest disturbances in Europe

The DFDE update resulted in greatly improved spatial and temporal coverage of reported forest disturbance data for Europe. The total number of individual records compiled by Schelhaas et al. (2003) was ~31,000 from 280 different sources. The new version of the DFDE contains 173,506 records from 600 sources (03/2022). Large improvements are noted for many countries, but especially for countries underrepresented before. Examples of these countries are Estonia, Latvia, Lithuania, Slovakia, Slovenia and Serbia. An overview of the cleaned time-series reported in the DFDE is shown in Figure 3.

3.2 | Time-series completeness and gap-filling

The average reported damage between 1950 and 2019 caused by all recorded disturbance agents in Europe was 43.8 Mm^3/year. This is based on the aggregation of reported time-series for 34 countries and five disturbance agents. Out of these 170 time-series, only 22% was labeled by experts as being complete, while 38% was labeled as incomplete and 39% as empty. Wind exhibited the most complete time-series (41% of the countries). While for all countries at least some information for fire exists, only 18% of the series were labeled as complete. For bark beetles, other biotic and other abiotic disturbance more than half of the time-series were empty, and around 15%–20% of the series were labeled as complete.

The gap-filled predictions based on reported data only (Figure 2) resulted in an average total damage of 62.1 million (M) m^3/year between 1950 and 2019. The predictions based on the expert's interpreted (zero-filled) time-series (Figure 2) showed an average total disturbance over the same period of 52.4 Mm^3/year. The values of variance explained by the models and the RMSE are displayed in Table 1. Figure 4 shows a comparison between reported data, data gap-filled with RF model trained on reported only and expert's interpreted time-series, respectively.

3.3 | Trends of forest disturbance in Europe

Disturbance data show strong fluctuations in magnitude (Figure 4), with large peaks driven by singular extreme events. Historically, those peaks are represented by windstorms, while in the last decade we observed a surge in bark beetle damage (Figure 3). We found a clear positive and significant trend in disturbance over time, with an average increase in total timber volume disturbed of approximately 845,000 m^3 per year between 1950 and 2019 (Table 2).

Wind is responsible for the most damage in European forests in the last 70 years, accounting for 46% of the total timber volume disturbed. The wind disturbance time-series is driven by individual extreme events such as the storms Vivian and Wiebke in 1990, Lothar and Martin in 1999, Gudrun in 2005, Kyrill in 2007 and Klaus in 2009; yet there are also years with high cumulative chronic damage. The data do not show strong patterns over time, and the trend in wind disturbance is weaker than for other disturbances (Table 2). The average wind disturbance over the whole study period is 24 Mm^3/year. Two decades, the 1990s and 2000s, had particularly high rates of wind disturbance (47.8 and 38.3 Mm^3/year, respectively, Figure 5).

Fire is the second most important disturbance in Europe's forests, accounting for 24% of the total timber volume damage over the study period. Fire impact has increased significantly between 1950 and 2019 across Europe (Table 2, Figure 5). Atlantic, East, and Central Mediterranean and Northern/Baltic regions show no significant trend, while the Alpine and Sub-Atlantic regions show a significant negative trend, meaning that fire disturbance decreased over the study period in these regions. All the other regions showed significant increasing trends. At the European level, we observed a sharp increase in fire disturbance in the 1970s, reaching its peak at the beginning of the 1990s (Figure 5). During the 1990s, chronic fire disturbance began to decrease. However, large peaks of strong individual disturbance years are evident from the 1990s onward, caused by extreme regional fire years. The estimated average timber volume damaged by fire between 1950 and 2019 is 12.5 Mm^3/

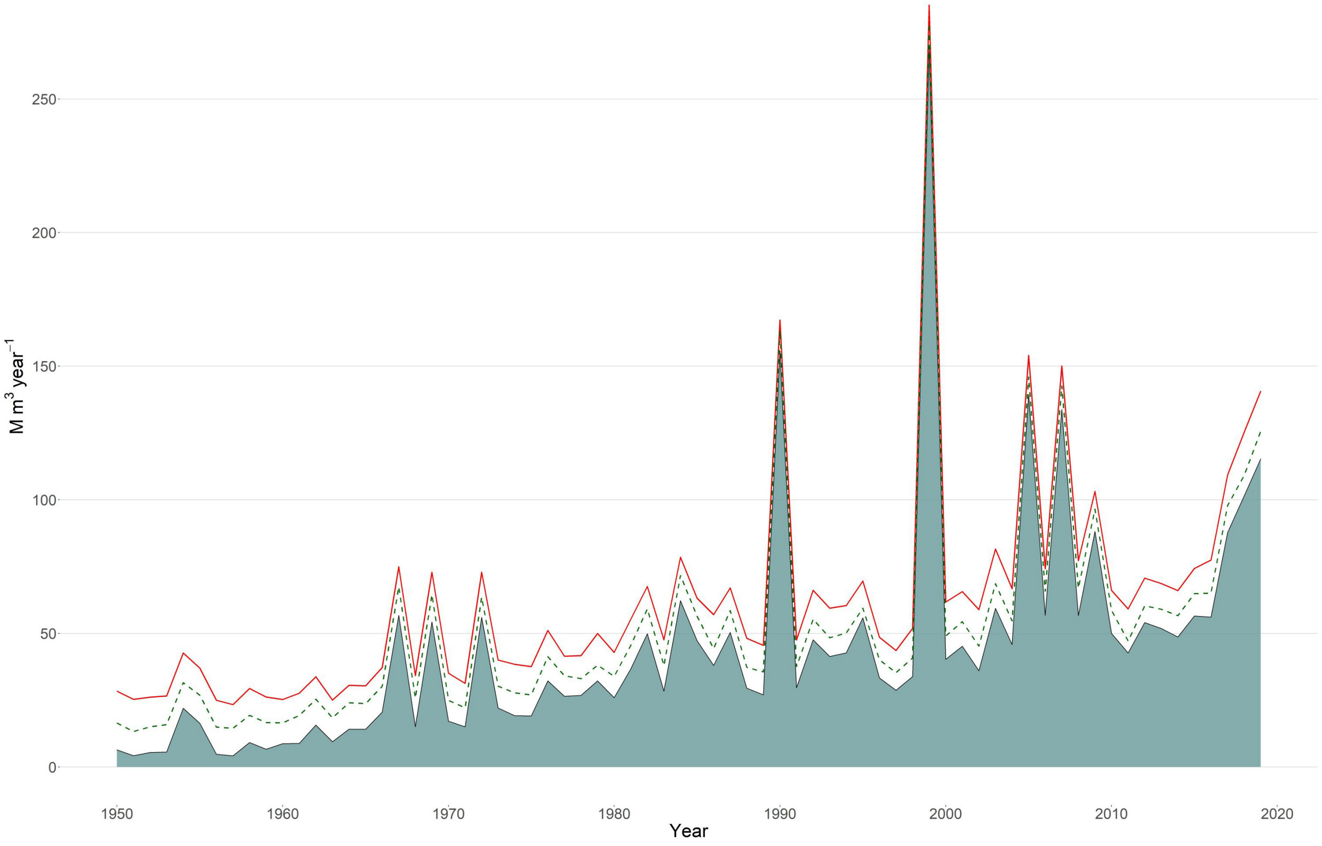

FIGURE 4 Comparison between reported data (grey area) and data gap-filled using RF models trained on reported only (red solid line) and expert's interpreted time-series (green dashed line), respectively.

TABLE 2 Mann–Kendall (MK) trend test and Sen's slope (SS) test parameters of gap-filled time-series based on expert interpretation. Parameters for each disturbance agent per ecozone as well as for their sum (total disturbance)

	Wind		Fire		Bark beetles		Other biotic		Other abiotic		Total disturbance	
Expert gap-filled	MK tau	SS	MK tau	SS	MK tau	SS	MKs tau	SS	MKs tau	SS	MK tau	SS
Europe	**0.47***	**309,294**	**0.35***	**99,609**	**0.64***	**182,897**	**0.82***	**134,773**	**0.53***	**46,313**	**0.64***	**844,998**
Alpine	0.35*	31,721	−0.4*	−953	0.72*	30,763	0.13	13,748	0.14	1060	0.56*	92,208
Atlantic	−0.08	0	0.23	62	0	0	0	0	0	0	0.07	14
East Med.	−0.13	−3	0.04	2294	0	0	0	0	0	0	0.02	1389
Central Med.	0.7*	10,996	0.22	20,300	0.75*	4364	0.78*	25,303	0.40*	2836	0.61*	91,680
Central Pannonic	0.56*	139,002	0.44*	13,226	0.53*	92,337	0.75*	78,782	0.44*	30,697	0.76*	407,953
Northern /Baltic	0.41*	43,351	−0.06	−344	−0.4*	−17,595	0.51*	3620	−0.1	−24	0.3*	43,871
Sub-Atlantic	0.19	24,605	−0.31*	−9174	0.52*	19,852	0.41*	6622	0.18	1066	0.37*	90,402
West Med.	0.18	0	0.29*	42,758	0	0	0	0	0	0	0.29*	49,020

Note: Europe indicates the sum over the 34 countries included in the study. MK test indicates the direction of the trend (between −1 and +1) and the * indicate the significance of the trend at $\alpha = .05$ confidence level. SS indicates the effect size, that is, the average magnitude of the trend's yearly change (in m^3). The parameters of the same tests on reported-only and gap-filled reported time-series are available in the supplementary materials 4.

Europe indicates the sum over the 34 countries included in the study (bold values).

year. 82% of the overall burned area over the study period is reported in Mediterranean ecozones (i.e., West, Central, and East Mediterranean together).

The timber volume damaged by bark beetles accounts for 17% of the total volume disturbed between 1950 and 2019. Recurring outbreaks were already taking place throughout the 1970s, 1980s and 1990s, but after 2000, the magnitude of bark beetle disturbance increased drastically, reaching an average of 23 Mm^3/year in the decade 2010–2019. The highest positive trends are reported in the Alpine, Sub-Atlantic, Central Mediterranean and Central Pannonic ecoregions, while trends in the Northern/Baltic ecoregion are negative. The ecoregions with the highest magnitude of average disturbance per year are the Central Pannonic and Alpine regions (Table 2).

Other biotic disturbances accounted for 8% of the total timber volume damaged. After the 1980s, we observed a sharp increase in other biotic disturbances (Figure 5). At European scale, we found a significant increase in other biotic disturbance of around 135,000 m^3 of damaged timber volume per year, that is the strongest positive trend across all disturbance agents (Table 2). The average disturbance caused by other biotic agents over the 70 years of the study period was 5 Mm^3/year.

The average timber volume damaged by other abiotic disturbance increased almost sixfold in 70 years, from around 630,000 m^3/year in the 1950s (1950–1959) to 3.7 Mm^3/year between 2010 and 2019. However, peaks in individual years are even higher, reaching up to 7 Mm^3 in 1980 and almost 13 Mm^3 in 2007. Other abiotic disturbance accounted for 6% of the total timber volume damaged between 1950 and 2019.

3.4 | Disturbance impacts on forest resources

Based on expert interpreted gap-filled data, the average amount of damaged wood from disturbances in Europe during the period 1950–2000 was 42.6 Mm^3/year. This represents 0.23% of the average GS for the same period. In the last two decades (2001–2019), the average timber volume disturbed across Europe increased to 78.5 Mm^3/year, corresponding to 0.27% of the average GS. Harvest data were available for the period 1961–2019. The average timber volume disturbed amounted to about 15% of the mean annual harvest in Europe for the period 1961–2000. The average timber volume disturbed for the period 2001–2019 accounted for 16% of the mean annual harvest for the 34 countries subject to this study. Figure 6 shows the decadal average SDI per country. A complete table with all reported and predicted values of SDI is available in the supplementary material 5.

4 | DISCUSSION

The stark increase of forest disturbances in the last two decades measured using RS data (Forzieri et al., 2021; Seidl et al., 2017; Senf et al., 2018) highlighted the need for ground-based data to better

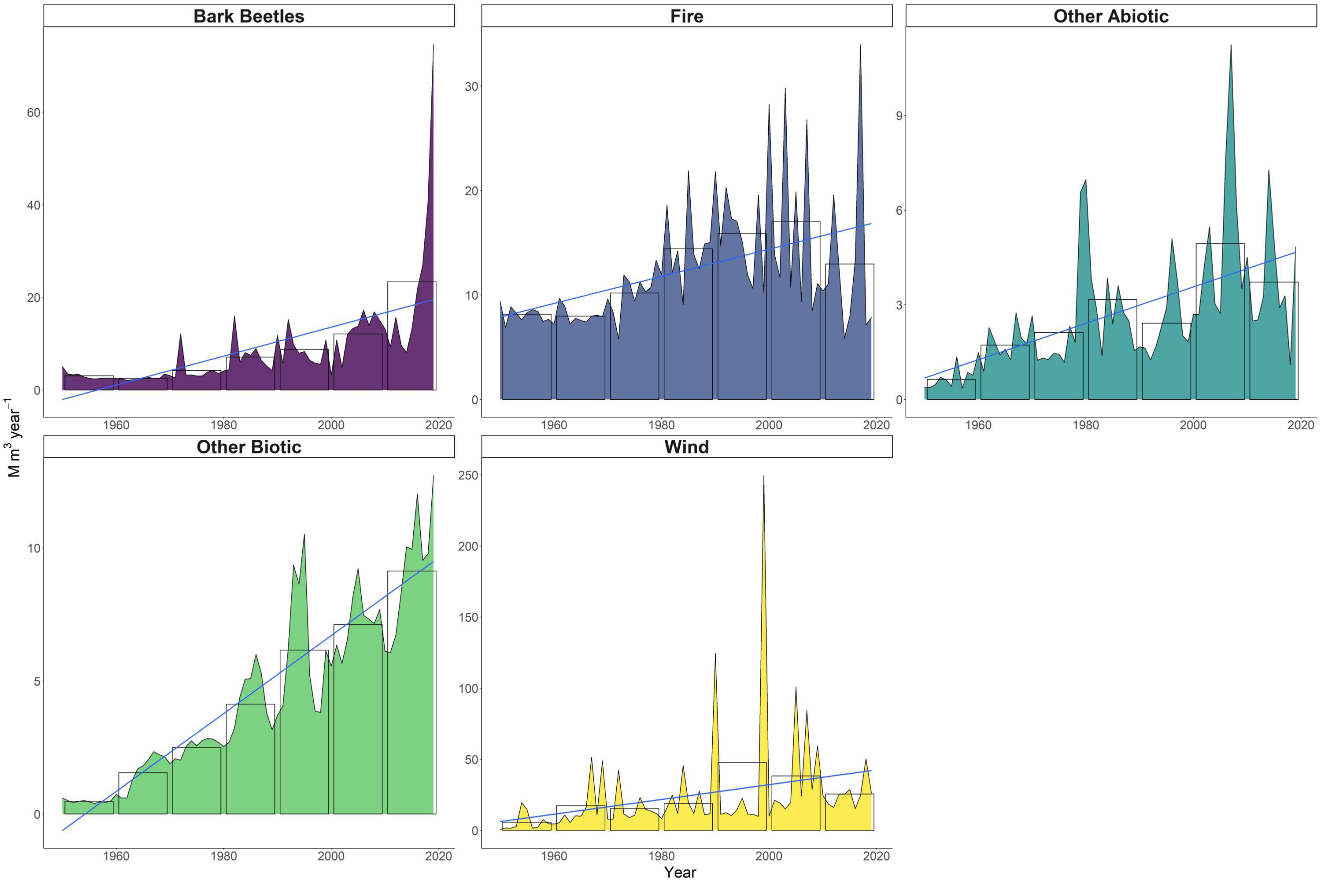

FIGURE 5 Expert's interpreted gap-filled time-series of disturbance drivers between 1950 and 2019. The values represent the sum of the 34 European countries object of this study. The bars represent a decadal average. The lines are linear models fitted to the decadal averages. The scales of the panel's y-axis differ for improving the visualization.

understand disturbance dynamics at the European scale, particularly with regard to the attribution of individual disturbance agents (Sebald et al., 2021). Moreover, the lack of empirical data limited the efforts of including disturbances in dynamic forest models (Machado-Nunez Morerio et al., 2022). This study greatly extended the coverage and completeness of empirical observation of forest disturbances in the DFDE. This effort constitutes an unprecedented data collection and synthesis of ground-based disturbance damage estimates across continental Europe. All data are publicly available and accessible at https://dfde.efi.int/db/dfde_app.php (Schelhaas et al., 2020).

4.1 | Forest disturbances in Europe over the past 70 years and their geographical and temporal changes

Windstorms caused the highest damage to timber volume in Europe in the last 70 years accounting for about 46% of the damage. The damage pattern is highly stochastic, with certain decades clearly showing higher damage than others. However, because both extreme events and chronic damage increased, wind-related disturbance increased overall. This observation is in accordance with observations from previous studies (Gregow et al., 2017; Senf & Seidl, 2021b). However, the causes behind this trend are unclear. There is some evidence of increases in maximum wind-speed (Usbeck et al., 2010) during extreme events and some studies predict a reduction in recurrence intervals of such events (i.e., more frequent extreme events) over Europe in a warming climate (Outten & Sobolowski, 2021). However, abiotic factors (e.g., soil, exposure, slope) and forest management have a great influence on wind risk in forests (Gardiner et al., 2010; Seidl et al., 2011), and changes in the forest resources over this period very likely contributed to the trend.

Forest fires are the best documented disturbance agent in Europe, with the most comprehensive timeseries available in dedicated databases. In Europe, forest fires affect mainly Southern regions, due to Mediterranean climate, flammable vegetation and rugged terrain (Pausas et al., 2008). Timber volume disturbed by fire showed an overall increase in Europe between 1950–2019. The fire-suppression policy adopted in the second half of the twentieth century initially showed positive results (Tedim et al., 2015). However, fire suppression, in combination with abandonment of rural areas and an increasingly urban society contributed to increasing fuel loads and fire ignition risks (Piñol et al., 2007). Improved detection and response efforts from the 1990s onward, followed in the 2010s by alternative management strategies such as prescribed burning (Montiel & Kraus, 2010), started decreasing fuel load, reducing

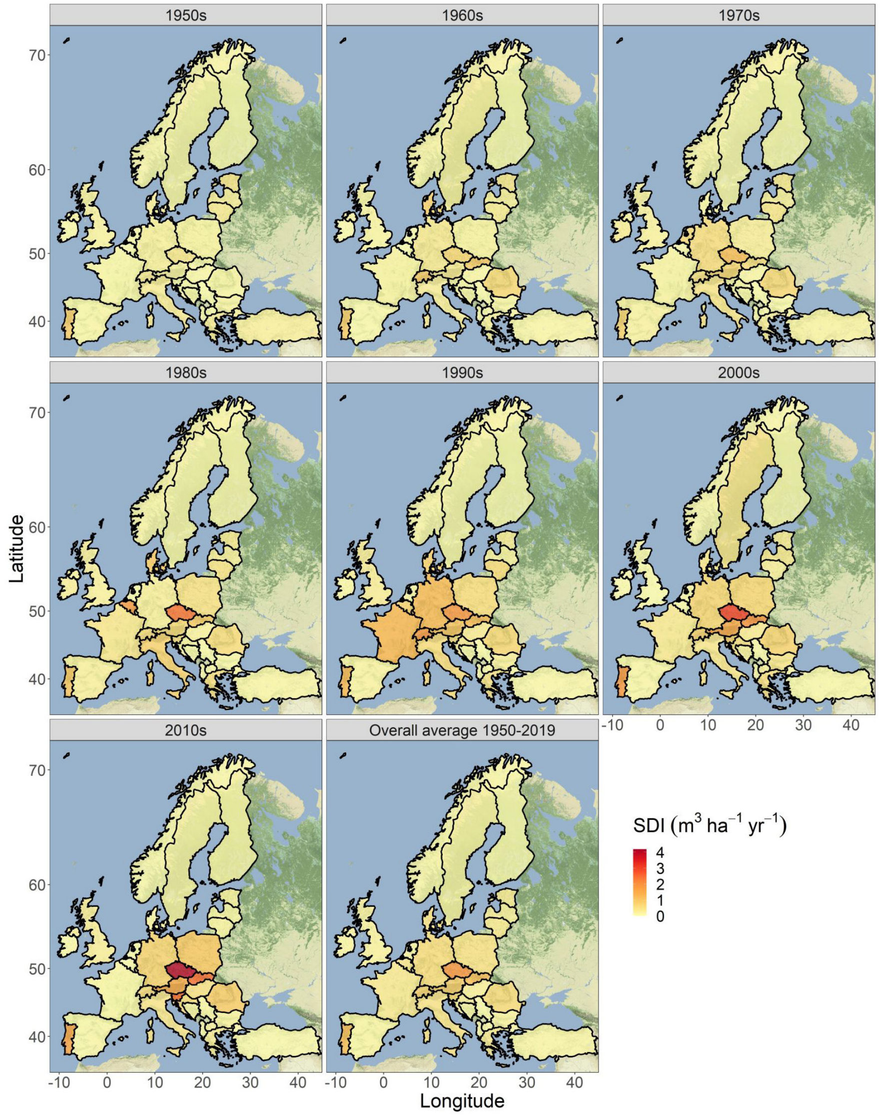

FIGURE 6 Decadal and overall (1950–2019) averages of countries SDIs based on experts' interpreted gap-filled time-series. Specific values are reported in supplementary material 5 together with values for the other time-series.

chronic fire disturbance (Doerr & Santín, 2016; Turco et al., 2016). This development is reflected in our study, showing a steep increase in fire disturbance from the 1960s until the 1990s and a subsequent decrease of damage in the years with chronic damage (Figure 5). However, this decrease was offset by individual extreme fire years, the so-called mega-fires (Linley et al., 2022). In addition, RS studies found relatively stable areas of burned forest in Europe (San-Miguel-Ayanz et al., 2022; Senf & Seidl, 2021c). Megafires happen when a combination of factors, both human- and climate-dependent (e.g., ignitions, continuous fuel loads, fire weather), result in a threshold being crossed, leading to extreme intensity and spread rates of fires (Jones et al., 2022; Pausas & Keeley, 2021). Under climate change we expect this threshold to be exceeded more frequently (Dowdy et al., 2017), likely further increasing the intensity and frequency of extreme fire events (Dupuy et al., 2020). However, the importance of individual drivers may vary across regions (Pausas & Keeley, 2021).

For bark beetle disturbance we found a strongly increasing trend. Schelhaas et al. (2003) reported that bark beetles were responsible for 8% of the total timber volume damaged by disturbances between 1950 and 2000. Over the period 1950–2019, they accounted for 17% of the total timber volume disturbed, mainly as a result of massive outbreaks in the last decade. In 2018, for instance, half of the German salvage logging was caused by bark beetle disturbance and in 2021 this value even rose to 81.4% (41 Mm^3—half of the total harvest; Destatis, 2022). In the Czech Republic, bark beetle disturbance equalled planned harvest (17 Mm^3) in 2018, and resulted in over-harvesting in 2019 and 2020 (23 and 25 Mm^3, respectively) (Fernandez-Carrillo et al., 2020; Hlásny, Zimová, et al., 2021). In 2019, the timber volume disturbed by bark beetle across Europe amounted to 70.1 Mm^3. During 2020 and 2021, beyond the temporal scope of this analysis, the trend of bark beetle damage kept increasing. Climate change has a strong amplifying effect on bark beetle populations, allowing for the completion of more generations per year (Baier et al., 2007), and extending their biological niche into higher elevations and latitudes (Jakoby et al., 2019). Moreover, the effect of other disturbances (e.g., drought) weakens the resistance of *P. abies* to beetle infestation. Weakened trees, in often overstocked, monospecific plantations established outside of *P. abies*' natural range, provide perfect conditions for bark beetle outbreaks (Hlásny, König, et al., 2021). However, the magnitude of trends in bark beetle disturbances differed across regions (see Table 2). Bark beetle disturbance is expected to further increase in the coming years in Europe (Hlásny, König, et al., 2021), intensified by climate change, particularly affecting regions where *P. abies* grows in low- to mid-elevation areas (Thom et al., 2017).

Other biotic agents often show similar sensitivity to climate change (Seidl et al., 2017; Turner, 2010), as changes in environmental conditions directly influence their life cycles and phenology. The trend of other biotic disturbances reported in our empirical time-series shows the highest relative increase among all disturbance agents investigated. This inter alia includes the impact of invasive alien pests such as ash dieback (Hymenoscyphus fraxineus; Enderle et al., 2019). However, very often biotic disturbances do not result in direct impacts on timber removals, but rather in the weakening of tree vitality and a decrease in general forest health (e.g., in the case of defoliating insects). This type of impact is frequently reported in terms of canopy area affected (ha), both at the regional (Sierota et al., 2019) and continental scale (FAO, 2020). In those cases, the effect of biotic disturbances was gap-filled in our analysis, because we know that certain regions suffered from biotic disturbance agents in specific years, but reported data were restricted to canopy defoliation and did not report on associated tree mortality. This highlights the importance of improving the reporting efforts for biotic disturbance agents as a key step to improve the scarcely available information on their dynamics (Honkaniemi et al., 2021).

Other abiotic disturbances include a variety of different disturbance agents. Snow and ice-storm disturbances in Europe are frequent in high-latitude regions and high-altitude areas (Suvanto et al., 2020). Those events mostly occur in autumn and winter, when temperatures are low and convective air movements favour a vertical air–temperature structure (typical for ice-storms; Nagel et al., 2017). While increasing global warming is expected to reduce the incidence of those events (Rumpf et al., 2022), climate change induced uncertainty (Lehtonen et al., 2016) and temporal variability of extreme events (e.g., late-spring or early-autumn frost and wet snow precipitation) might increase the damage caused by those agents, especially on broadleaved species when already or still with leaves on the canopy (Nagel et al., 2017). Hail and rime are stochastic events, and together account for limited disturbance in Europe's forests in terms of timber volume disturbed. Drought is one of the main climate induced disturbances in Europe and most of the globe (Hartmann et al., 2022; Peters et al., 2021; Senf et al., 2020). However, drought damage is difficult to identify in ground-based assessments, as it has a wide range of effects on trees and often plays a key role as a predisposing factor to other disturbances, which are then ultimately responsible for tree mortality. For this reason, there are few quantitative field-based studies on direct drought damage available for Europe, and its contribution to our disturbance data set is very limited. Improved monitoring of drought damage of trees will likely have to rely mostly on RS observations of tree vitality (Thonfeld et al., 2022) complemented by close to real time ground-based measurements of growth responses with, for example, automated dendrometers (Salomón et al. 2022).

4.2 | Completeness of reported observations and methodological implications

Large-scale disturbance events, such as extreme windstorms or mega-fires, create damages for millions of euros (Hanewinkel et al., 2013) and very high hazards to people and society, beyond altering ecosystem functioning. Naturally, these major events have a high probability of being assessed and reported. However, we suspect that a great deal of the chronic damage remains unreported, as suggested by the fact that only 22% of the reported time-series was considered to be complete, compared with 38% labeled as incomplete. Gaps in a time-series can be interpreted in two ways: either no disturbance happened or some disturbance of a certain magnitude happened and has not been reported. For instance, in the Czech Republic we have a very long time-series with few gaps, where we know with some confidence that there was no bark beetle damage in years without reporting (expert interpretation and Brázdil et al., 2022). Therefore, we assumed no bark beetle damage in those years. In Sweden and Finland, there are no records for bark beetles in the first decades of the time-series, despite evidences of past bark beetle outbreaks in those countries (Annila, 1969). Hence, we assumed those damages were not quantitatively reported, and filled those gaps statistically. Explicitly entering a zero value for years with no damage reported in the time-series that were labeled as complete had considerable consequences in training the models and the resulting estimates. The first effect is that there is no gap-filling in the complete time-series, disabling the possibility that the gap-filling inserts (extreme) values in the empty years. As a second effect, the models are trained on data that contain years with zeros associated with certain predictor values, lowering the predictions under comparable conditions in the gap-filling. The two types of models used allowed us to produce a range of total disturbance damage estimate for Europe, including unreported damage. The prediction accuracy varied depending on disturbance agent and ecozone. For instance, for bark beetle damage in the Central Pannonic ecozone, the model trained on the reported data explained more variance compared with the one trained on zero-filled expert interpretations (85.1% and 62.02%, respectively). This suggests that in years where we placed a zero, actually some bark beetle damage took place because the accuracy of the model decreased. In contrast, the bark beetle models for the Sub-Atlantic ecozone showed the opposite pattern: the one trained on reported data explained less variance than the one trained on zero-filled data (23.37% and 55.08%, respectively), suggesting that in the zero-filled years there was no actual damage. Given this variability we assume that, depending on the specific cases, the gap-filled total damage will lie within the range of the two scenarios developed here.

4.3 | Comparison with remote sensing trends

In recent years, the development of new technologies, availability of satellite imaging data and increased computational capacity have improved RS techniques, enabling RS-based analyses of disturbance dynamics at continental scale (Forzieri et al., 2021; Francini et al., 2022; Senf & Seidl, 2021a). Many of those studies report an increasing trend of disturbance over the last 40 years. Our findings are in line with these trends, with an overall increase being evident also in our empirical data. Satellite products have the advantage that the information is spatially explicit, and that time-series are continuous and consistent across the entire continent. Therefore, satellite-based time-series have less gaps, and underreporting is more related to the technique applied to identify disturbance patches than to missing reporting, like in our database. RS-based recognition of disturbances detect canopy changes and express them in units of area (ha) or as NDVI anomalies (Kern et al., 2022), which makes it difficult to compare them directly with our results (expressed in m^3 of timber disturbed). However, despite recent advances in RS, the main limitation of RS-based analyses of forest disturbance remains the attribution of disturbance agents (Hermosilla et al., 2015; Senf & Seidl, 2021a, 2021c). Especially, differentiating natural disturbances from anthropogenic management remains problematic (Sebald et al., 2021; Senf & Seidl, 2021c). Moreover, passive satellite imaging does not always have the sufficient resolution to identify small disturbance-induced gaps and chronic damage, which are typical for many ecosystems in Europe. The discussed pros and cons of empirical observations and RS highlight the potential for a complementary application of both sources to improve the overall understanding of natural disturbance dynamics in Europe.

4.4 | Disturbance impacts on growing stocks and harvesting

The average disturbance impact on GS increased by 17%, from 0.23% in the period 1950–2000 to 0.27% in the period 2001–2019. At the same time, the GS level in Europe increased from an average of 18.7 billion m^3 in the period 1950–2000, to an average of 29.1 billion m^3 in the period 2001–2019 (FOREST EUROPE, 2020). Similarly, disturbance related shares in the total harvest amounts increased from 15% in the period 1961–2000 to 16% in the period 2001–2019, despite the harvest level over the same time span almost doubled. In most European countries, harvest is below the increment, which implies a further increase in GS for the near future, although there are signs that the build-up of GS is saturating (Nabuurs et al., 2013). At the same time, the harvest level is unlikely to increase drastically (Lerink et al., 2022). However, with ongoing climate change, disturbance damage is likely to increase further, given the strong climate dependency of fire, bark beetles and other biotic agents. Thus, we can expect even higher shares of GS being affected by disturbances in the future, and higher shares of salvage logging in the harvested wood.

The increase of disturbance impacts on forest resources strongly affects planned forest management in Europe, causing disruptions of long-term planning, and making it difficult to ensure sustainable harvesting and ecosystem services provisioning (Messier et al., 2019). Moreover, at the local scale the effects are much larger, impacting heavily forest enterprises (which might lose their entire mature GS), with tremendous consequences for local economies and human wellbeing in affected regions. Finally, those disruptions are expected to cause severe fluctuations of the international timber market, with potential negative implications for the European bioeconomy.

The standardized disturbance index (m^3/ha/year) allows us to compare the decadal average disturbance incidence with the country's average net annual increment. In the Czech Republic, for example, on average over the last 20 years around 4 m^3/ha/year have been lost because of disturbances, constituting 1/3 of the increment (~12 m^3/ha/year; Hlásny, Zimová, et al., 2021), greatly impacting on ecosystem functioning and related services, such as the carbon cycle and biodiversity.

4.5 | Implications for EU policies

European forests play a key role in the European climate-change mitigation strategy (European Green Deal, 2019) and several other proposed regulations: the Biodiversity Strategy (European Commission, 2021), the revision of the LULUCF Regulation that aims at strengthening the carbon sink function (Herold et al., 2021), the Nature Restoration law (European Commission, 2022a) and the Sustainable Finance Initiative (European Commission, 2022b); the latter two steering with legally binding criteria. Moreover, there are growing expectations in storing additional carbon in harvested wood products, in providing renewable energy (European Commission, RED-II, 2021) and their contribution of avoided emissions when substituting carbon-intensive materials (Churkina et al., 2020; Leskinen et al., 2018), although uncertainties remain (Harmon, 2019).

However, all these policy goals could be threatened by the increased impacts of disturbances documented in our study. We found a significant increase of all disturbance causes in Europe.

Increasing disturbance-caused mortality could in fact transform European forests from being a carbon sink to become a net carbon source (Albrich et al., 2022), as previously observed following large-scale disturbances in other continents (Dymond et al., 2010; Hicke et al., 2012). Such changes in the forest carbon cycle can already be observed for European disturbance hotspots (e.g., the Czech Republic, Common Reporting Format, Czechia, UNFCCC, 2022).

Several forest management options have been proposed to improve the climate change resilience of European forests (e.g., Larsen et al., 2022; Nabuurs et al., 2017; Verkerk et al., 2020). Nevertheless, increasing disturbance regimes have the potential to offset the additional climate mitigation potential derived from improved forest management practices (FSOS UNECE-FAO, 2021).

4.6 | Critical evaluation of uncertainty

The information compiled here stem from a wide variety of sources, resulting in a considerable degree of heterogeneity in the data. Despite the careful analysis of sources and the consultation with national experts, inconsistencies in the data remain. For instance, countries may have different reporting methods, and most of the selected sources assess damaged timber volume resulting from disturbances by quantifying salvaged timber. On the one hand, salvage logging is common for large disturbance events in Europe, yet distributed small-scale chronic damage might go unreported or attributed to regular harvesting. On the other hand, focusing on salvage logging after disturbances may also lead to an overestimation of timber volume disturbed, as forest owners sometimes extract healthy trees in salvage operations due to tax exemption incentives. Burned area (ha) is the common reporting unit for fire disturbance (San-Miguel-Ayanz et al., 2013). By converting it to m^3 of damaged timber to make it comparable with other disturbance agents we may have introduced a bias due to missing country-specific FCFs. However, the countries which report the highest yearly incidence of fire do in fact report specific FCFs.

It is worth mentioning that since the late 1990s—early 2000s some countries improved their efforts in reporting disturbances, thereby reducing some of the uncertainties associated with earlier work. In fact, these more recent monitoring programs by governmental institutions allowed us to achieve the more robust disturbance time-series reported here.

4.7 | Recommendation and outlook

Forest disturbances are increasing rapidly in Europe. This increase greatly impacts European forests and the services they provide to society, especially at local scale. Moreover, disturbances may counteract efforts that are being made to improve forest management under climate change and increase the climate change mitigation function of forests. Therefore, strategies to cope with increasing disturbances should be placed at the core of future European forest management and policy.

The first step to adapt forests to increased climate-induced natural disturbances is to install a harmonized, consistent and close-to-real-time pan-European monitoring and reporting system of forest disturbances. Such a system is pivotal for understanding the complex interplay at the forest-climate-disturbance nexus, and for exploring effective alternative management strategies to ensure the sustainable provisioning of ecosystem services to society. There are already good examples of reporting systems in place, implemented by a few countries, which can be used as starting point for harmonized continental-scale efforts. A combination of RS and ground-based observations is necessary to achieve such consistency of monitoring and reporting. Special efforts are needed to understand the dynamics of disturbance drivers that are expected to increase in the future due to the effects of climate change, such as drought and biotic agents. Missing the opportunity of understanding, predicting and addressing disturbance risks will compromise the achievement of Europe's climate targets.

AUTHOR CONTRIBUTIONS

Marco Patacca, Marcus Lindner and Mart-Jan Schelhaas developed the idea of the paper. Sergey Zudin built the database structure and repository. Marco Patacca collected the data, updated the database, ran the analyses, made the figures and wrote the paper. Mart-Jan Schelhaas, Marcus Lindner, Gert-Jan Nabuurs, Rupert Seidl gave major contributions in writing the paper. Dominik Thom, Rupert Seidl and Masa Zorana Ostrogović Sever provided suggestions for the analyses. All other authors contributed with data, expert interpretations and feedback on the manuscript.

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CONFLICT OF INTEREST

All the authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The raw data that support the findings of this study are openly available in the Database of Forest Disturbances in Europe (DFDE) at https://dfde.efi.int/db/dfde_app.php (Patacca et al., 2021; Schelhaas et al., 2020). The database is hosted by the European Forest Institute (EFI). At country scale, numerical values of (i) the cleaned time-series we constructed by processing raw reported data from the DFDE, (ii) the time-series gap-filled based on the reported data, (iii) the time-series gap-filled based on expert-interpretation, and (iv) the expert labeling for each time-series per disturbance driver and country are publicly available at https://github.com/MarcoPatacca/DFDE_manuscript_Patacca_etal2022 together with the code developed to produce the main figures of the paper and the gap-filling procedure.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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