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Storm and fire disturbances in Europe: Distribution and trends

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Abstract

Abiotic forest disturbances are an important driver of ecosystem dynamics. In Europe, storms and fires have been identified as the most important abiotic disturbances in the recent past. Yet, how strongly these agents drive local disturbance regimes compared to other agents (e.g., biotic, human) remains unresolved. Furthermore, whether storms and fires are responsible for the observed increase in forest disturbances in Europe is debated. Here, we provide quantitative evidence for the prevalence of storm and fire disturbances in Europe 1986–2016. For 27 million disturbance patches mapped from satellite data, we determined whether they were caused by storm or fire, using a random forest classifier and a large reference dataset of true disturbance occurrences. We subsequently analyzed patterns of disturbance prevalence (i.e., the share of an agent on the overall area disturbed) in space and time. Storm- and fire-related disturbances each accounted for approximately 7% of all disturbances recorded in Europe in the period 1986–2016. Storm-related disturbances were most prevalent in western and central Europe, where they locally accounted for >50% of all disturbances, but we also identified storm-related disturbances in south-eastern and eastern Europe. Fire-related disturbances were a major disturbance agent in southern and south-eastern Europe, but fires also occurred in eastern and northern Europe. The prevalence and absolute area of storm-related disturbances increased over time, whereas no trend was detected for fire-related disturbances. Overall, we estimate an average of 127,716 (97,680–162,725) ha of storm-related disturbances per year and an average of 141,436 (107,353–181,022) ha of fire-related disturbances per year. We conclude that abiotic disturbances caused by storm and fire are important drivers of forest dynamics in Europe, but that their influence varies substantially by region. Our analysis further suggests that increasing storm-related disturbances are an important driver of Europe's changing forest disturbance regimes.

KEYWORDS
climate extremes, fire, forest mortality, Landsat, windthrow

1 | INTRODUCTION

Europe's forests have been managed by humans for centuries (McGrath et al., 2015). They are vital for today's human well-being as they provide important ecosystem services to society (Forest Europe, 2015). Those services include timber production, the regulation of carbon and water cycles as well as the provision of habitat and recreation space, among others. The vast majority of Europe's forests is under some form of management, with less than 1% of the forest area being considered primeval (Sabatini et al., 2018). High management intensity in combination with high relevance of forests to society has led to the emergence of a command-and-control management paradigm (Holling & Meffe, 1996) in the 20th century, that is, the notion that once a problem is perceived, a solution can be developed and implemented to solve the problem. A widely held view under this paradigm was that management is able to determine stand structure and composition, while controlling natural drivers of forest dynamics such as disturbance. More recently, large waves of natural disturbances (Seidl et al., 2014) and the recognition of a rapidly changing social-ecological environments have led to the adoption of new management paradigms such as resilience thinking (Nikinmaa et al., 2020; Rist & Moen, 2013), that is, approaches better able to address the complexities, nonlinearities and uncertainties of coupled human and natural systems. These emerging paradigms *inter alia* explicitly acknowledge the role of natural drivers of forest dynamics, such as disturbance (Seidl, 2014). Consequently, they also require quantitative information on these processes and their variation in space and time as foundation for management decision-making.

Natural disturbances are triggered by a wide variety of agents. In Europe's forests, storms, fires and bark beetles are the most important natural disturbance agents (Schelhaas et al., 2003; Seidl et al., 2014; Sommerfeld et al., 2018). Storms and fires are abiotic disturbances, that is, disturbances caused by the inanimate environment. Tree mortality from these disturbances is directly caused by physical factors (e.g., stem breakage in a storm event, overheating of the cambium in a wildfire). Forest disturbances related to storm include the breakage and uprooting of trees from strong gusts (Mitchell, 2013), which we here refer to as *storm-related disturbances*. In Europe, storm-related disturbances most often result from cyclonic weather systems moving in west-east direction over Europe (Donat et al., 2010). While these systems have a large footprint and affect considerable land areas simultaneously, more localized storm-related disturbances occur in downbursts, foehn storms or tornados (Dotzek et al., 2009). In addition, storm-related disturbances can also result from snow storms (Nykänen et al., 1997). Fire disturbances include all tree mortality resulting as a direct and indirect consequence of fire (Michaletz & Johnson, 2007), here termed *fire-related disturbances*. These include several fire types common in Europe (surface and crown fires) as well as fires caused by both human and natural ignition sources (Ganteaume et al., 2013). Other abiotic disturbances not in the focus here are avalanches, landslides, earthquakes or volcanic eruptions (Moore & Allard, 2011; Sommerfeld et al., 2018), and also drought as direct and indirect agent of tree mortality (Senf, Buras, et al., 2020).

Storm- and fire-related disturbances are often directly linked to climatic extremes. As such, they are highly climate-sensitive processes that are likely to change as climate change continues (Seidl et al., 2017). The distribution and trends of storm- and fire-related disturbances remain difficult to assess, however, as natural disturbances are per definition rare, extreme events that require long-term observations for robust inference. Several trans-national efforts have compiled information on both storm- and fire-related disturbances (Forzieri et al., 2020; San-Miguel-Ayanz et al., 2012; Schelhaas et al., 2003), but most of these databases are collections of individual cases with a high selection bias, and are neither spatially explicit nor comprehensive. Selection bias arises from higher availability of data in countries with well-established and long-running forest monitoring programs, and access restrictions to data in some countries. Moreover, selection bias is likely to become larger when moving back in time, making it challenging to derive robust trend estimates. Hence, it remains unclear how important abiotic forest disturbances are, in fact, for European forest dynamics. Answering this question is of high importance, because of an ongoing discussion whether increasing forest disturbances reported for Europe (Senf et al., 2021; Senf et al., 2018) are the result of increased utilization of forest resources or increased natural disturbances (Ceccherini et al., 2020; Palahí et al., 2021). Shedding light on the distribution and trends of individual disturbance agents is thus of key relevance for Europe's current forest policy, and provides and important baseline for managing forests for an uncertain future (Ammer et al., 2018; Anderegg et al., 2020; Angelstam & Kuuluvainen, 2004; Mori, 2011; Seidl et al., 2016).

Here, our aim was to improve the quantitative understanding of storm- and fire-related disturbances in Europe's forests by addressing four research questions: (1) What is the prevalence of storm- and fire-related disturbances in Europe? (2) Does the prevalence of storm- and fire-related disturbances vary in space? (3) Does the prevalence of storm- and fire-related disturbances vary over time? (4) What is the total forest area affected by storm- and fire-related disturbances? To address these four questions, we predicted whether disturbed patches were storm- or fire-related for approximately 27 million instances across Europe, covering the time period from 1986 to 2016. Subsequently, we estimated the prevalence of both storm- or fire-related disturbances, that is, the area disturbed by storm- and fire-related disturbances relative to the total area disturbed, and analyzed how prevalence varies in space and time. We thus determined where European forest dynamics had been dominated by storm and/or fire-related disturbances, and whether this changed over time. We finally present an estimate of the absolute forest area affected by both disturbance agents by jointly analyzing the prevalence of storm- and fire-related disturbances with a sample-based estimate of forest disturbance rates in Europe (Senf et al., 2021).

2 | DATA AND METHODS

2.1 | Disturbance patches

We used an existing pan-European forest disturbance map created from Landsat satellite data at a grain of 30 m for the years 1986–2016 (Senf & Seidl, 2021) and available under https://zenodo.org/record/4570157#.YFByJC337OQ (version 1.0.0). The map depicts for each pixel if and when a disturbance occurred, regardless of disturbance agent. The map is based on the supervised classification of spectral trajectories, and full details on the processing workflow are given in Senf and Seidl (2021). To identify individual disturbance patches from the disturbance map, we delineated annual patches using a queen contiguity. That is, we combined all pixels sharing either an edge or node and occurring in the same year into a patch. In this analysis we noted several instances where areas clearly created by a single disturbance event were broken into two or more patches due to uncertainty in the estimated disturbance year. This happened, for example, in cases where a fire occurred in August, but for some parts of the fire, the underlying satellite data were recorded in July (and those parts of the fire were thus detected only in the following year). Other instances occurred as a result of the Landsat 7 scan line corrector failure (Wulder et al., 2016), where missing observations were gap-filled with data from the following year. Those artefacts are known from previous research (Hermosilla et al., 2015a) and we here applied a spatial filter to address them: We iteratively merged all patches that shared at least one edge, and had consecutive disturbance years, into one continuous patch. We then assigned the disturbance year of the final patch by majority vote across all pixels. The merging of adjacent patches reduced the overall number of disturbance patches from approximately 36 million to approximately 27 million for all of Europe in the period 1986 to 2016. The median patch size across all patches was only 0.45 ha, with 99% of the disturbed patches being smaller than 10 ha. For a comprehensive description of the European forest disturbance regimes, we refer to Senf and Seidl (2021).

2.2 | Reference data of abiotic disturbances

We here present a model that predicts the probability of being caused by either wind or fire for each disturbance patch occurring in Europe in the time period 1986–2016. In order to calibrate the model, instances of true wind- and fire-related disturbances were needed. As no spatially exhaustive dataset existed that could be used as calibration data, we combined visual interpretation of the disturbance map, Landsat data and high-resolution satellite images with different European storm and fire databases to identify true occurrences of storm- and fire-related disturbances. Specifically, we checked for each storm entered in either the European Forest Institute's database on forest disturbances in Europe (Schelhaas et al., 2003) or the FORWIND database (Forzieri et al., 2020) whether we could locate the storm in the European forest disturbance map. The European Forest Institute's database on forest disturbances in Europe is non-spatial, but includes an exhaustive collection of windthrow events in Europe compiled from grey literature sources. The FORWIND database is a collection of spatially explicit data on recent large-scale windthrow events, mostly collected through local authorities, with varying data quality (i.e., ranging from automatic classification of satellite data to manual interpretation of aerial imagery or inventory data). We used the year of the storm and the approximate location to search for clusters of disturbance patches that could be unambiguously linked to the storm event. We additionally used online-search tools to search for scientific papers, reports or newspaper articles providing further information on the location of the storm and corroborate the final decision. Once a disturbance patch could be linked to a storm event without doubt, we labeled the patch as storm-related. Using this approach, we could identify 7723 reference patches that were unambiguously storm-related (Figure 1; see also Figure S1a for further details). Storm-related reference patches were found across all of Europe, with a higher density in central and western-Europe. Yet, we also identified several storm-related reference patches in northern Europe, eastern Europe and south-eastern Europe.

In a similar manner as for storm-related disturbances, we used the European forest fire information system (EFFIS) database (San-Miguel-Ayanz et al., 2012) and visual interpretation of the disturbance map to identify true occurrences of fire-related disturbances. Information in the EFFIS database are based on the MODIS burnt area product (Justice et al., 2002), which has low spatial resolution, high commission error and only dates back to 2001. Despite these limitations, the EFFIS database was well suited to identify true burnt patches in the detailed European forest disturbance map. Fires in the European disturbance map were generally well recognizable due to their relatively large patch size compared to other disturbances in Europe, and due to their irregular shape relative to harvest operations. We also used high-resolution imagery, whenever available through open map services, to identify burn scars or other obvious features to further corroborate our assessment. Through this approach, we could identify 3641 reference disturbance patches as being unambiguously related to fire (Figure 1; see

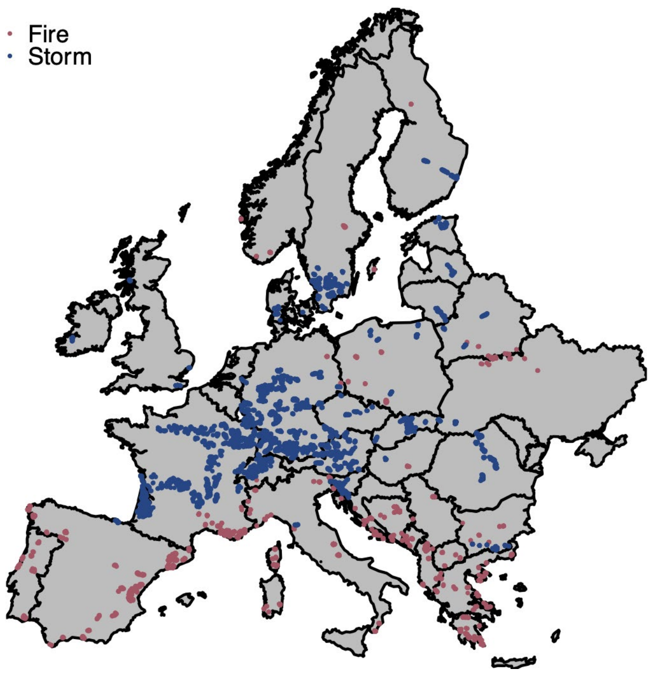

FIGURE 1 True occurrences of storm- and fire-related disturbances collected via visual interpretation and the comparison of the European forest disturbance map to existing databases on natural disturbances in Europe. n = 3641 for fire, and n = 7723 for storm. See Figure S1 for details on the visual interpretation

also Figure S1b for further details). Fire-related reference patches were more present in southern- and south-eastern Europe, but we also identified several fires in eastern and northern Europe.

2.3 | Predictors of disturbance agent

We created a set of predictors to model the probability of each disturbance patch being related to either storm or fire, or neither (i.e., harvest, biotic disturbances). Predictors were largely based on previous regional studies mapping disturbance agents in Europe (Oeser et al., 2017; Sebald et al., 2021) and included four spectral, three spatial and three landscape predictors (see Table S1 for a comprehensive list of all predictors). Spectral predictors considered were the patch-average absolute change magnitude (i.e., the difference in spectral signal before and after disturbance), change duration (i.e., the duration of spectral decline during disturbance) and change rate (i.e., magnitude divided by duration) in the Normalized Burn Ratio (Kennedy et al., 2010). The Normalized Burn Ratio is a normalized difference index based on shortwave-infrared reflectance, and is highly sensitive to forest disturbances (Senf et al., 2015). The spectral predictors give information on the abruptness and intensity of a disturbance, and thus can be helpful in differentiating between agents of change (Hermosilla et al., 2015b; Kennedy et al., 2015; Schroeder et al., 2017). We used the Normalized Burn Ratio of the year prior to disturbance as normalizing constant. Spatial predictors included the size and the fractional dimension index of each patch. The fractional dimension index is a measure of the spatial complexity of a disturbance patch that is independent of patch size and thus preferable over perimeter-based indices. Landscape predictors included two measures on the pulse dynamics of each patch in relation to its surrounding landscape and one predictor on the patch configuration in the surrounding landscape. The assumption behind these predictors is that natural disturbances tend to be clustered in space and time (Turner & Gardner, 2015), that is, they occur in pulses, whereas regular management tends to be uniformly distributed over time (Sebald et al., 2021). To capture this notion, we calculated the relative area disturbed occurring in the same year as the focal patch for the surrounding landscape of each individual disturbance patch. High values indicate that most disturbances between 1986 and 2016 occurred in the same year for a given landscape (a disturbance pulse typical for natural disturbances), and small values indicate low disturbance activity in the surrounding landscape in the same year. The landscape extent for these analyses was defined as a radial kernel with a 5-kilometer radius based on previous analyses (Sebald et al., 2021). We calculated the landscape predictors for the year the focal patch was disturbed, and for one year preceding and one year following this year. This was done to account for uncertainties in the year of disturbance assigned to each patch. We moreover included the number of patches in the surrounding landscape as predictor, giving further indication of whether the pulse occurred in several smaller patches (as would be typical for wind) or in one large patch (as would be typical for fire). We finally included the center x and y coordinate of each patch in the regression to account for broad scale gradients (i.e., temperature gradient from south to north, increasing continentality from west to east) in the relationship between predictors and response.

2.4 | Attribution model

We calibrated a random forest model predicting the probability of each patch being either storm- or fire-related, using the occurrence data on storm- and fire-related disturbances described above (see Section 2.2). As no true absences of both storm- and fire-related disturbances were available, we used a pseudo-absence approach commonly applied also in species distribution modeling (Pearce & Boyce, 2006). In particular, we drew a random sample of patches approximately the same size as the reference sample from the whole population of disturbance patches as pseudo-absences (Barbet-Massin et al., 2012). This sample of pseudo-absences represents the whole gradient of disturbances in Europe against which the true occurrences of storm- and fire-related disturbances can be compared to.

Using the calibrated random forest model, we predicted the probability of being storm- or fire-related for each disturbance patch in Europe over the period 1986–2016. We derived three probabilities from the random forest model: (i) the probability of being storm-related (p_s), (ii) the probability of being fire-related (p_f), and (iii) the probability of being neither storm- nor fire-related (here called other; p_o), with $p_o + p_s + p_f = 1$. The "other" class p_o includes all disturbances not related to storm or fire, and consists mostly of harvest and biotic disturbance (often co-occurring with drought), and to a lesser degree also of more locally important disturbance types such as avalanches and land use conversions. While probabilities are powerful means for expressing uncertainties, we also assigned categories (i.e., storm- or fire-related, other) in order to calculate prevalence in subsequent analyses. As we here favored a high omission error over a high commission error, we decided for a relative strict probability threshold of $p_s > 0.5$ and $p_f > 0.5$. In other words, we were conservative in assigning a disturbance patch to either storm or fire, compared to the widely used majority vote (i.e., $p_s > 0.33$ and $p_f > 0.33$). While this strict threshold will lead to the omission of some true storm- or fire-related disturbances in our analysis, it prevents the false attribution of patches as storm- or fire-related. We assessed overall model performance using a fivefold spatial block cross validation (Valavi et al., 2019) and report the area under the curve (AUC) for both storm- and fire-related disturbances, as well as overall. We also calculated commission and omission error rates for the discrete categories. We visually compared spatial polygons of wind disturbances recorded in the FORWIND database (Forzieri et al., 2020) with our results. Furthermore, we compared the total area burnt reported in the EFFIS database (San-Miguel-Ayanz et al., 2012) with the total area burnt derived from our maps (data download from: https://effis.jrc.ec.europa.eu; last accessed: 28

October 2020). We note that while we harnessed these two datasets to identify reference patches, we did not use them directly in our modeling. Consequently, these comparisons constitute evaluations of our results against independent datasets.

2.5 | Prevalence analysis and area estimates

From the attributed disturbance map, we calculate the prevalence of storm- and fire-related disturbances. We divided the storm- and fire-related disturbance area by the total area disturbed, that is, $a_s/(a_s + a_f + a_o)$ and $a_f/(a_s + a_f + a_o)$. We derived these prevalence metrics for the full time period and each year separately at both the European and country level. For assessing the spatial and temporal variability in prevalences, we aggregated prevalences at a grid of 50-km hexagons and derived overall and annual maps. We quantified trends in the prevalence of storm- and fire-related disturbances at both the European and country level using a Sen's slope estimator, which is a time-series linear trend estimator that is insensitive to outliers such as extreme storm or fire years (Wilcox, 2010).

We finally derived area estimates for storm- and fire-related disturbances by jointly analyzing the prevalences derived in this study with a sample-based estimate of European forest disturbance rates (Senf et al., 2021). Specifically, we multiplied the annual disturbance rates (and their uncertainties) derived by (Senf et al., 2021) using a well-established sample-based time series interpretation approach (Cohen et al., 2010, 2016; Senf et al., 2018) with the prevalences of storm- and fire-related disturbances calculated in this study to derive agent-wise disturbance rates. Multiplying those agent-wise disturbance rates with Europe's forest area (227 million ha, according to Forest Europe, 2020) then yields an unbiased estimates of the total and average annual forest area disturbed by agent, including well-quantified uncertainties.

3 | RESULTS

3.1 | Mapping abiotic forest disturbances across Europe

The model predicting the occurrence of storm- and fire-related disturbances performed well (AUC = 0.98 for both storm- and fire-related disturbances). The resulting discrete categories had an overall error rate of 0.08 (i.e., an overall accuracy of 92%), with a commission error rate of 0.07 for storm-related and 0.13 for fire-related disturbances (Table 1). That is, the model assigns a false occurrence of wind-related disturbances for 7% of the disturbance patches, and a false occurrence of fire-related disturbances for 13% of the disturbance patches. The omission error rate was 0.10 for storm-related and 0.24 for fire-related disturbances (Table 1). That is, the model missed a true occurrence of wind-related disturbances for 10% of the disturbed patches, and a true occurrence of a fire-related disturbance for 24% of the disturbed patches. We note that the errors reported here are model errors and not map errors derived from an independent probabilistic sample.

Applying the model for each of the approximately 27 million disturbance patches in Europe, the resultant map indicates whether disturbance patches are storm- or fire-related, or neither (i.e., other; Figure 2). Visual inspection of the map revealed a good match with known storm events that occurred in Europe in the last three decades, such as the storm Kyrill in 2007 in Western and Central Europe (Figure 2a), the ice storm of 2014 in Slovenia (Figure 2f), the High Tatra windthrow in 2004 (Figure 2g), or storm Gudrun in southern Sweden in 2005 (Figure 2h). Fire-related disturbances occurred mostly in southern and south-eastern Europe (e.g., Spain and Greece; Figure 2c,e), but we also detected individual fires in Fenno-Scandinavia (such as the Västmanland wildfire in Sweden in 2014; Figure 2b) and eastern Europe (e.g., Ukraine, Belarus, Poland). Individual smaller fires were also found in mountain regions, such as in the Italian Alps (e.g., see Figure 2f) or in the Carpathians (e.g., see Figure 2g).

The predictors of highest importance for discriminating storm- and fire-related disturbances from other disturbances were the landscape-scale pulse dynamics, the size and fractional dimension of a disturbance patch, the latitude (i.e., north-south gradient), and the pre-disturbance spectral value in the Normalized Burn Ratio (see Figure S2 for further details). Both storm- and fire-related disturbances showed strong pulse dynamics, that is, they occurred in clusters of patches in their immediate (<5 km) surrounding (Figure S3). Other disturbances (i.e., mostly harvest) showed muss less spatiotemporal clustering. Storm- and fire-related disturbances also tended to be larger and more complex in shape compared to other disturbances, which was especially true for fire-related disturbances (Figure S3). The pre-disturbance spectral value in the Normalized Burn Ratio was lower for fire-related disturbances than

TABLE 1 Model errors for attributing storm- and fire-related disturbances, estimated from true occurrences and background data (a total of 17,031 disturbance patches) using fivefold spatial block cross validation

Predicted (*n*)	Observed (*n*) Other (Harvest, biotic disturbances, etc.)	Observed (*n*) Storm	Observed (*n*) Fire	Commission error rate
Other (Harvest, biotic disturbances, etc.)	8422	545	243	0.08
Storm	313	6073	116	0.07
Fire	37	138	1144	0.13
Omission error rate	0.04	0.10	0.23	

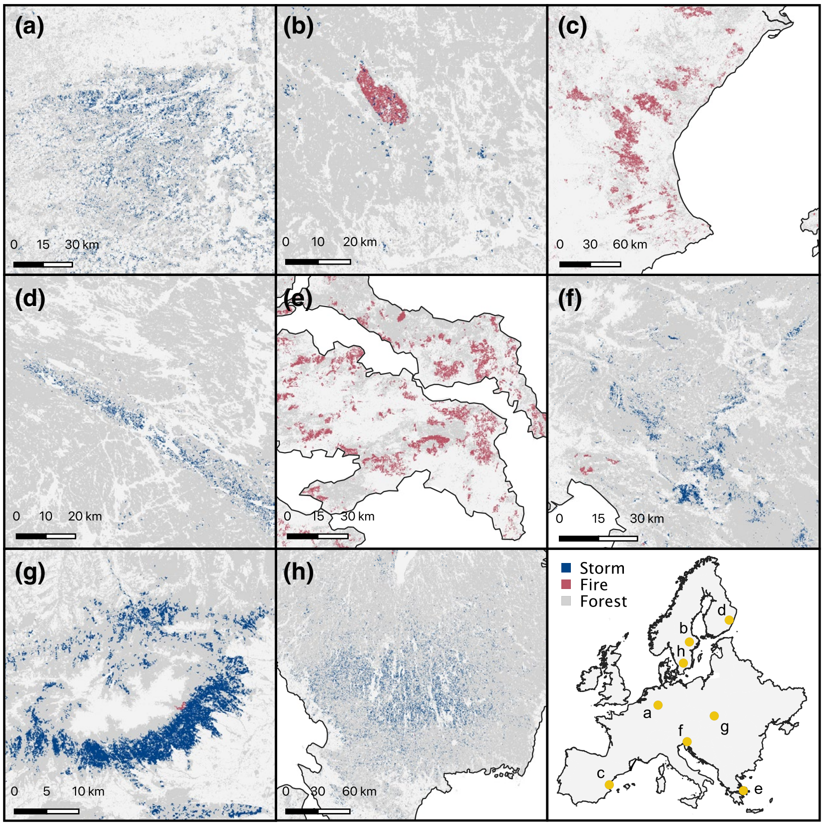

FIGURE 2 Storm- and fire-related disturbances mapped across Europe, with examples from (a) storm Kyrill in Germany in 2007; (b) the 2014 Västmanland wildfire in Sweden; (c) forest fires in south-eastern Spain; (d) a series of summer-thunderstorm causing widespread tree breakage in Finland in 2010; (e) forest fires in Greece; (f) an ice-storm in Slovenia in 2014 and a series of smaller fires along the Italian-Slovenian border; (g) one of the largest storm-related disturbance patches in Europe, the High Tatra wind-throw in 2004 in Slovakia; (h) large-scale wind disturbance from storm Gudrun in southern Sweden in 2005. Black lines represent coast lines. [Correction added on 9 June 2021, after first online publication: Figure 2 has been modified.]

for storm-related disturbances and other disturbances (Figure S3), which suggests a more open canopy structure in areas affected by fire than in areas affected by storm.

3.2 | Prevalence of abiotic disturbances

Over the period 1986–2016, storm- and fire-related disturbances each accounted for 7% of the total disturbed area recorded in the European forest disturbance map. The two most important abiotic disturbances (i.e., storm and fire grouped together) thus caused 14% of all disturbances occurring in the period 1986–2016 in Europe. However, there was high temporal variation in prevalence at the European level, especially for storm-related disturbances (Figure 3). Several years had very high shares of storm-related disturbances, with more than 15% of all European disturbances caused by storms in those years (e.g., 1990, 2000, and 2007). We note, however, that due to the annual resolution of the underlying data and the use of satellite images from the peak of the vegetation period, storm-related disturbances might be attributed to the following year if the storm occurred late in the year. This is the case in the year 2000, where the signal of storm Lothar (December 1999), is mapped.

We detected a significant increase in the prevalence of storm-related disturbances over time, with an average increase of 0.2 percentage points per year (Sen's slope estimator; $z = 2.58$, $n = 31$, $p = 0.01$). While the median storm prevalence for the period 1986–2001 was 3%, it increased to 6% for the period 2002–2016. The median prevalence of storm-related disturbances thus doubled between the first and the second half of the observation period. Fire-related disturbances occurred less in pulses and were more

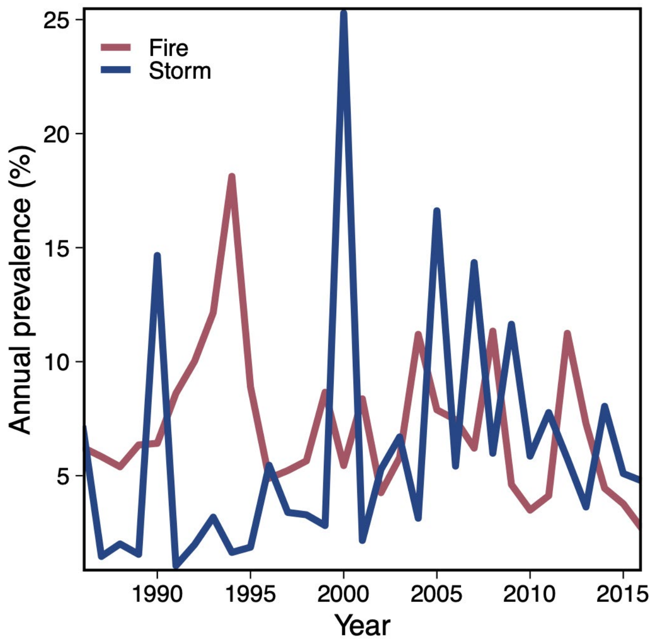

FIGURE 3 Annual prevalence of storm- and fire-related disturbances in Europe's forests. Prevalence here expresses the share of the total forest area disturbed in a given year that is caused by the respective agent

constant over time (Figure 3), with annual prevalence values generally below 15% but above 5%. One exception was the year 1994, where nearly 20% of all disturbances in Europe were caused by fire (Figure 3). Fire prevalence showed no significant trend over time (Sen's slope estimator; $z = -1.77$, $n = 31$, $p = 0.07$), with a median prevalence of 6% for both the periods 1986–2001 and 2002–2016.

Spatial variation in the prevalence of storm- and fire-related disturbances in Europe was high (Figure 4). High prevalence of storm-related disturbances (i.e., 25%–50% over the full period) was mainly found in central and western Europe (e.g., Germany, France, Switzerland, United Kingdom) as well as in some parts of eastern Europe (e.g., Romania). For some regions in Germany and France, and parts of Slovenia, storm-related disturbances contributed to more than 50% of all disturbances recorded for the period 1986–2016. In those regions, storm-related disturbances were thus the dominant driver of forest dynamics, also exceeding the influence of forest management. Fire-related disturbances were highly prevalent throughout most parts of southern and south-eastern Europe as well as in parts of Ukraine and some regions of the Alps. Very high prevalence of fire-related disturbances (i.e., >50% over the full period) were found in south-eastern Spain, southern Greece, along the coast of Croatia and in Montenegro. In those regions, fire-related disturbance was the main driver of forest dynamics.

Aggregating prevalence to the country level further underlined the high spatial variability in the occurrence of storm- and fire-related disturbances (Figure 5). Taken together, storm- and fire-related disturbances caused less than 25% of all disturbances in approximately 70% of the countries of Europe (25 out of 35). Out of the 10 countries with prevalences larger than 25%, four were clearly dominated by storm-related disturbances and six were clearly dominated by fire-related disturbances. Fire-related disturbances were dominating the top five countries affected by abiotic disturbances, where they caused between 30 and 50% of all disturbances in the period 1986–2016. Notably, a mixture of both storm- and fire-related disturbances is rare in Europe.

The analysis of abiotic disturbance agents at the country level again highlighted the high temporal variability in abiotic disturbances (Figure 6). Both storm- and fire-related disturbances create distinct pulses in some years, while having low prevalences in other years. This pattern was again more pronounced for storm-related disturbances than for fire-related disturbances. However, fire exhibited a higher temporal variation at the country-level than at the European-level (i.e., compare Figures 6 and 3). Several large-scale storm events are clearly visible in the country level analyses, including the storm Vivian/Wiebke (1990), Lothar (1999) and Kyrill (2007) affecting many countries simultaneously in central and western Europe (e.g., Austria, Denmark, Belgium, France, Germany, Switzerland). For fire-related disturbances, high prevalence years (i.e., annual prevalence >50%) were less synchronized than storm-related disturbances.

Trends for disturbance prevalence differed by agent, with positive trends occurring predominantly for storm-related disturbances and negative trends occurring predominantly for

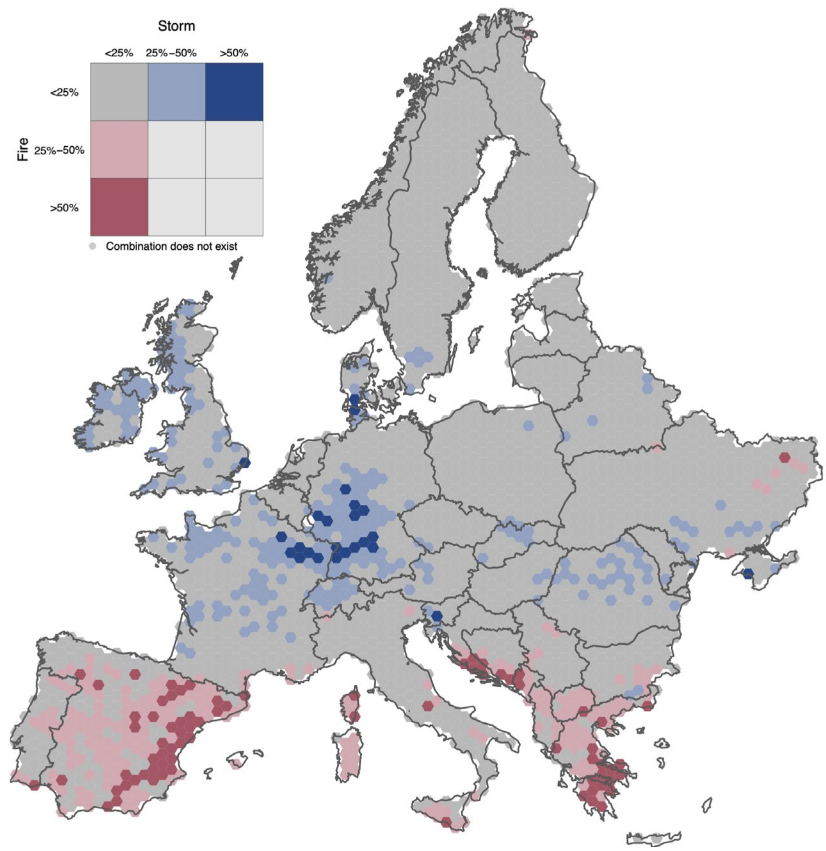

FIGURE 4 Spatial variability in the prevalence of storm- and fire-related disturbances over the period 1986–2016. Note that light-grey combinations do not exist in the data, that is, there is no overlap between high prevalence in storm- and fire-related disturbances in Europe. See Figures S4 and S5 for annual prevalence maps by agent

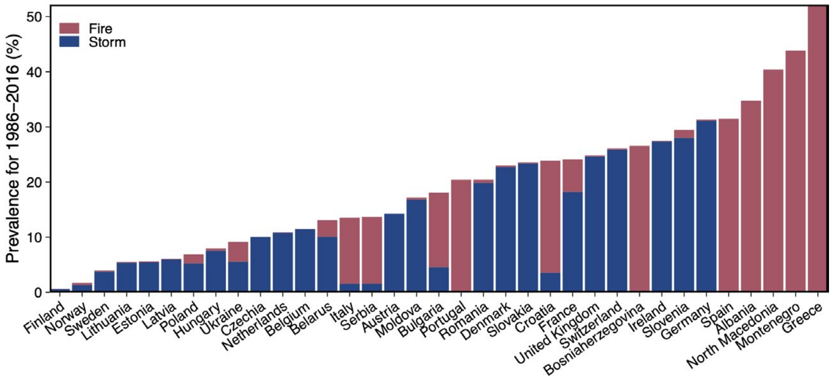

FIGURE 5 Prevalence of storm- and fire-related disturbances over the period 1986–2016 aggregated by countries

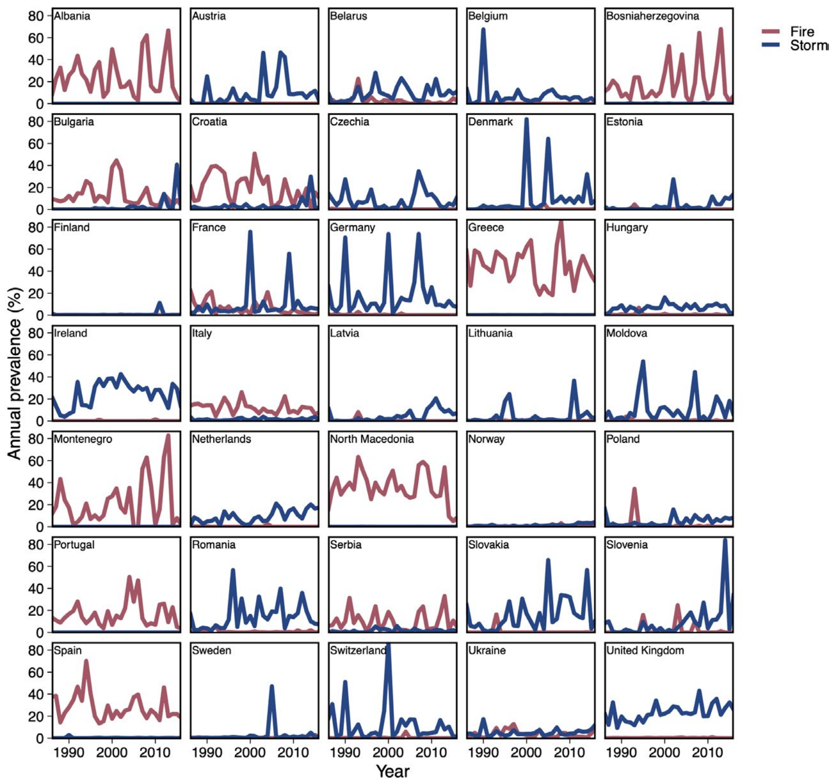

FIGURE 6 Annual prevalence of storm- and fire-related disturbances for individual countries

fire-related disturbances (Table 2). We identified 15 countries with a significant positive trend in storm-related disturbance prevalence, but no country with a significantly increasing trend in fire-related disturbance prevalence. For fire-related disturbances, we found five countries with a significant negative trend. More than half of the countries in Europe showed no trend in fire-related disturbance prevalence.

3.3 | Area disturbed by storm and fire

We estimate that over the period 1986–2016, storm-related disturbances affected a total area of 4.0 (3.0–5.0 million) ha forest, and fire-related disturbances affected a total area of 4.4 million (95% credible interval: 3.3–5.6 million) ha forest (Table 2). This is an average of 127,716 (97,680–162,725) ha of storm-related disturbances per year (0.06 [0.04–0.07] % of the total forest area), and an average of 141,436 (107,353–181,022) ha of fire-related disturbances per year (0.06 [0.05–0.08] % of the total forest area). Comparing the first half of the observation period (1986–2001) to the second half (2002–2016), we found that the area of storm-related disturbances increased by approximately 930,000 ha from 1,528,417 (1,280,975–1,775,859) ha to 2,459,885 (2,092,065–2,827,706) ha (Figure 7). The area affected by fire-related disturbances, however, remained stable between both periods (Figure 7).

3.4 | Comparison to other datasets

Our map identified all storm events recorded in the FORWIND database, but the spatial match between our map and the polygon-based representation of storms in FORWIND varied (Figure 8). While

TABLE 2 Prevalences and trends of storm- and fire-related disturbances for European countries

Country	Storm-related disturbances						Fire-related disturbances					
	Prevalences			Sen's slopes			Prevalences			Sen's slopes		
	1986–2016	1986–2001	2002–2016	Trend (% points year^{-1})	z-value (n = 31)	p-value	1986–2016	1986–2001	2002–2016	Trend (% points year^{-1})	z-value (n = 31)	p-value
Albania	0.00	0.00	0.00	0	−0.21	0.84	20.11	26.35	15.20	−0.23	−0.61	0.54
Austria	5.41	3.58	9.36	0.32	3.03	0.00	0.00	0.00	0.00	0	−1.4	0.16
Belarus	8.31	6.34	10.93	0.26	2.48	0.01	1.50	2.28	0.91	−0.05	−1.75	0.08
Belgium	4.37	3.67	5.45	0.04	0.71	0.48	-	-	-	-	-	-
Bosnia and Herzegovina	0.00	0.01	0.00	0.00	−0.07	0.94	10.87	11.16	8.98	0.07	0.31	0.76
Bulgaria	0..33	0.08	0.62	0.03	3.81	0.00	8.58	11.70	6.58	−0.17	−2.07	0.04
Croatia	1.67	1.42	1.79	0.05	1.7	0.09	19.08	26.00	13.81	−0.61	−1.97	0.05
Czech	6.99	6.56	8.58	−0.04	−0.37	0.71	0.00	0.00	0.00	0	−1.51	0.13
Denmark	3.55	2.03	6.99	0.30	4.64	0.00	0.00	0.00	0.00	0	1.41	0.16
Estonia	1.26	0.27	3.98	0.15	3.74	0.00	0.00	0.00	0.00	0	0.58	0.56
Finland	0.17	0.10	0.23	0.01	2.62	0.01	0.02	0.03	0.01	0	−2.96	<0.01
France	5.16	4.00	5.54	0.11	2.65	0.01	5.18	6.53	2.97	−0.31	−3.43	<0.01
Germany	10.56	9.57	12.95	0.09	0.51	0.61	0.00	0.19	0.00	0	−3.13	<0.01
Greece	0.04	0.03	0.04	0.00	−0.09	0.93	44.76	53.36	36.27	−0.5	−1.46	0.14
Hungary	6.77	6.24	8.04	0.10	1.39	0.16	0.05	0.17	0.00	0	−1.88	0.06
Ireland	28.27	18.40	28.33	0.25	0.92	0.36	0.00	0.00	0.00	0	0.73	0.46
Italy	1.10	0.97	1.52	0.03	1.33	0.18	12.22	13.51	8.40	−0.2	−2.62	0.01
Latvia	1.90	0.24	7.45	0.30	3.98	0.00	0.00	0.00	0.00	0	−0.93	0.35
Lithuania	1.30	0.58	1.92	0.07	2.79	0.01	0.00	0.00	0.00	0	1.49	0.14
Moldova	4.65	5.94	4.65	0.16	1.43	0.15	0.00	0.00	0.00	0	−0.55	0.59
Montenegro	0.00	0.00	0.00	0.00	2.03	0.04	15.64	14.06	15.64	0.19	0.42	0.67
Netherlands	7.61	5.81	14.46	0.44	3.71	<0.01	0.00	0.00	0.00	0	−1.91	0.06
North Macedonia	0.00	0.00	0.00	0.00	−0.19	0.85	33.80	37.54	28.83	−0.34	−1.36	0.17
Norway	0.70	0.27	1.43	0.07	4.11	<0.01	0.06	0.03	0.42	0	1.48	0.14
Poland	3.21	1.34	6.78	0.21	3.3	<0.01	0.12	0.55	0.01	−0.02	−3.57	<0.01
Portugal	-	-	-	-	-	-	13.29	13.50	12.89	−0.07	−0.37	0.71
Romania	11.53	5.42	15.17	0.37	2.35	0.02	0.32	0.35	0.32	0	−0.24	0.81
Serbia	1.10	0.92	1.25	0.03	1.53	0.13	8.08	9.55	3.48	−0.03	−0.1	0.92

(Continues)

TABLE 2 (Continued)

Country	Storm-related disturbances						Fire-related disturbances					
	Prevalences			Sen's slopes			Prevalences			Sen's slopes		
	1986–2016	1986–2001	2002–2016	Trend (% points year^{-1})	z-value (n = 31)	p-value	1986–2016	1986–2001	2002–2016	Trend (% points year^{-1})	z-value (n = 31)	p-value
Slovakia	11.34	6.85	14.60	0.41	2.38	0.02	0.00	0.00	0.00	0	0.32	0.75
Slovenia	4.58	1.83	11.17	0.46	3.42	<0.01	0.00	0.00	0.00	0	0.68	0.5
Spain	0.09	0.07	0.13	0.00	1.81	0.07	24.84	28.89	22.29	−0.36	−1.46	0.14
Sweden	0.81	0.54	1.20	0.04	3.3	<0.01	0.05	0.12	0.02	0	−1.26	0.21
Switzerland	5.53	4.66	6.05	−0.02	−0.24	0.81	0.00	0.00	0.00	0	−0.08	0.94
Ukraine	4.06	3.72	4.95	0.13	2.72	0.01	2.11	2.93	1.41	0	−0.07	0.95
United Kingdom	22.37	20.35	25.64	0.42	3.09	<0.01	0.07	0.11	0.06	0	0.41	0.68

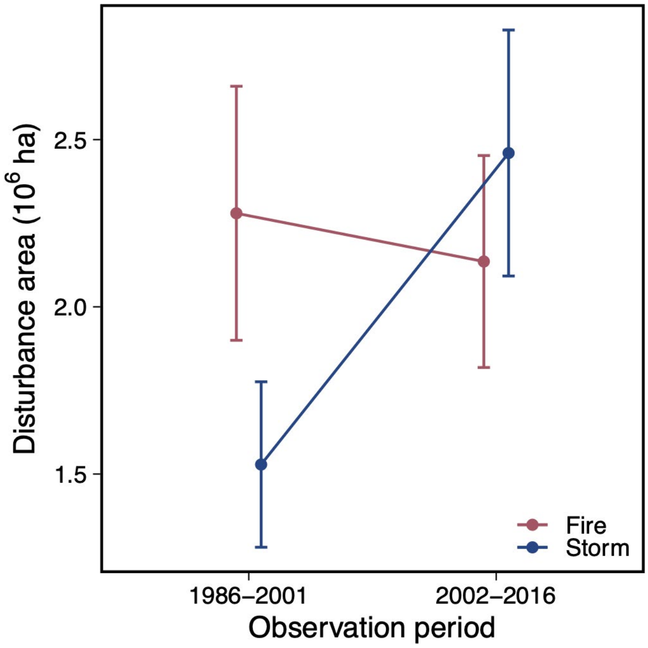

FIGURE 7 Sample based estimates of the total area of storm- and fire-related disturbances in the first and second half of the observation period

some storms recorded in the FORWIND database match perfectly with our maps (e.g., the High-Tatra wind-throw in Slovakia or storm Kyrill in Germany; first two rows in Figure 8), we identified many storm-related disturbances in our map that were not included in the FORWIND database (e.g., higher density of storm patches following storm Gudrun in Sweden in our map compared to the FORWIND database; third row in Figure 8). We note, however, that the FORWIND database is not an exhaustive database and depends strongly on the quality of external data sources (i.e., whether polygons were created by digitalization of aerial images or by automatic classification of satellite imagery). A direct comparison between our spatially comprehensive product and the FORWIND database is thus difficult.

Comparing our maps of fire disturbance to the EFFIS database we found considerable differences in the absolute area burnt (mean difference in annual burnt area of −19,186 ha). This deviance was expected, given the different aims of our maps and the EFFIS database (i.e., conservative estimate versus full reporting). Nevertheless, the annual area burnt per country as reported in the EFFIS database correlated highly with the annual fire area mapped in our study (Figure 9), indicating that the overall ranking of countries and the overall spatial distribution of fires matched well between our map and the EFFIS database.

4 | DISCUSSION

Europe's forests are general perceived as being dominated by humans (Curtis et al., 2018). Yet, natural disturbances have long been an integral driver of their dynamics (Schurman et al., 2018), and

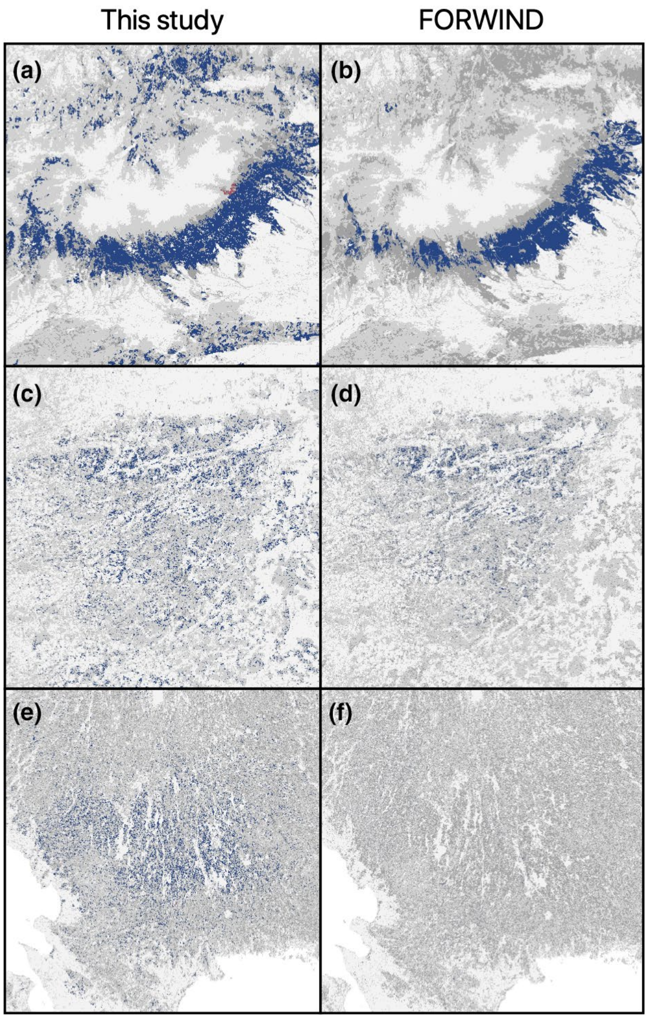

FIGURE 8 Comparison between wind-throw polygons of the FORWIND database and storm-related disturbances mapped in this study. The first row (a/b) shows the High Tatra wind-throw in Slovakia (see also figure 2g) with a good spatial match between both maps. The second row (c/d) shows storm Kyrill in Germany (see also figure 2a), also indicating a good match between both products. The third row (e/f) shows storm Gudrun in Sweden (see also figure 2h), with large differences in extent between both maps

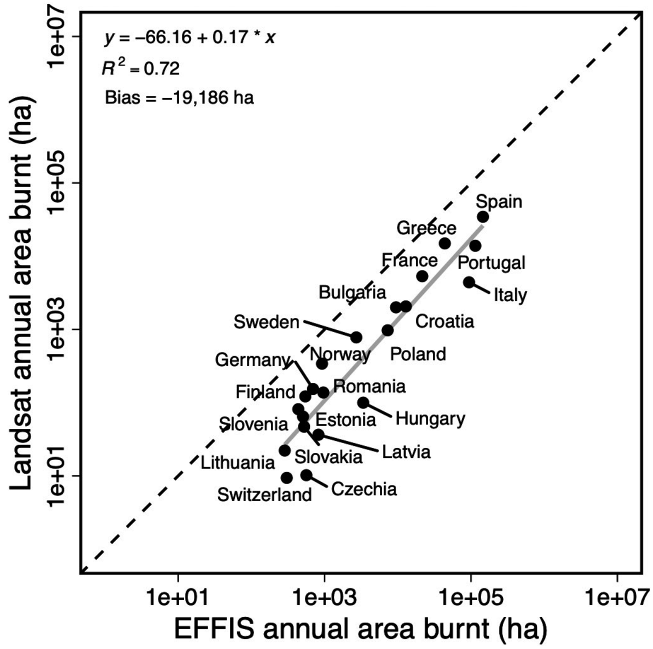

FIGURE 9 Comparison between the annual area burnt in the EFFIS database and annual area burnt derived from fire-related disturbances mapped in this study

have manifold positive impacts on forest ecosystems, such as increasing structural and species diversity (Hilmers et al., 2018; Senf, Mori, et al., 2020; Thom & Seidl, 2016). Recent increases in forest disturbances across Europe (Senf et al., 2018; Senf and Seidl, 2021) have triggered debates on how to address natural disturbances in management (Thorn et al., 2019). This debate, however, is lacking a sound evidence basis, as little data on the large-scale prevalence of natural disturbances in Europe were available to date. We here filled this gap by providing the first consistent continental-scale dataset on the two most important abiotic disturbance agents in Europe.

We highlight that both storm- and fire-related disturbances are important drivers of forest dynamics in Europe, but that their importance varies widely in space. While both storm- and fire-related disturbances caused only 14% of all disturbances recorded in the period 1986–2016 in Europe, they dominated forest dynamics (i.e., prevalence >50%) in several regions of the continent in the past three decades. In turn, this result also suggests that for the majority of Europe's forests, the disturbance regime is dominated by causes other than fire and storm. Those other causes might include other abiotic agents such as drought, avalanches, landslides, earthquakes, or volcanic eruptions (Moore & Allard, 2011; Sommerfeld et al., 2018); and also biotic disturbances, such as bark beetle outbreaks. Yet, prevalence of other natural disturbances, including bark beetle, has been much lower than for storm- and fire-related disturbances (Schelhaas et al., 2003), which might, however, change in the future with increasing drought-related pulses of excess mortality (Senf, Buras, et al., 2020). We thus suggest that the majority of disturbances in Europe is caused by humans, which is in line with previous analyses (Curtis et al., 2018; Senf et al., 2018).

The prevalence of both storm- and fire-related disturbances estimated here is higher than suggested in previous studies (8%; Schelhaas et al., 2003), which illustrates the relevance of a wall-to-wall analysis as the one presented here. We note, however, that a direct comparison to previous estimates is difficult, because they are frequently based on harvested timber volume and not on area disturbed. Storm- and fire-related disturbances had similar prevalence values in our analysis, suggesting that their influence on European forest dynamics is of comparable magnitude. This finding contradicts previous assessments, which report a higher importance of storm-related disturbances for overall forest dynamics (Schelhaas et al., 2003). The influence of storms and wildfires differs widely in space, however, and shows a clear separation between the two disturbance agents, with wind mainly dominating in central and western Europe and fire in southern Europe. This finding is important as many disturbance agents interact (Burton et al., 2020; Seidl et al., 2017), which, however, seems not to be the case for storms and fire in Europe. Our results moreover suggest differences in the temporal variation between storm- and fire-related disturbances, with a higher temporal variability in storm-related disturbances compared to a steadier occurrence of fires.

We found that the prevalence of storm-related disturbances has increased since the mid-1980s, whereas the prevalence of fire-related disturbances has remained constant over time. This resulted in an average increase in forest area affected by storm-related disturbances, whereas the total forest area affected by fire-related disturbances remained stable over the observation period. An increasing importance of storm-related disturbances has been suggested before based on statistical analysis of harvesting reports (Gregow et al., 2017). Our analysis here provides the first continentally consistent and scientifically rigorous evidence of such an increasing importance of storms in Europe. Increases in storm-related disturbances could be caused by increasing storm frequency and intensity (Haarsma et al., 2013; Leckebusch et al., 2006), but also by increasing susceptibility of forests to storms (Seidl et al., 2011). Also climate change could play a part, for example, via decreasing periods of frozen soils, which in turn decreases the anchorage of trees (Usbeck et al., 2010). The stable or even decreasing trend of fires is consistent with data in the EFFIS database, which suggests a decrease in burnt area but a slight increase in the number of fires. This is, however, in contrast to reports on increasing forest growing stock affected by forest fires in Europe (Schelhaas et al., 2003; Seidl et al., 2014). The decrease in burnt area might be explained by more efficient early-warning and fire detection systems, as well as by improved firefighting capacities. Nonetheless, the past years (i.e., 2017–2020) have been characterized by intensive forest fires throughout Europe, as hotter droughts consistently trigger extreme fire years (Seidl et al., 2020; Senf, Buras, et al., 2020). Fire could thus become more important under climate change.

We used remote sensing to provide a first wall-to-wall analysis of abiotic disturbances in Europe. While remote sensing has been applied to identify causal disturbance agents in several case studies in Europe before (Oeser et al., 2017; Sebald et al., 2021), we here provide the first continental-scale application of such an approach. We demonstrate the importance of predictors characterizing the spatial form and landscape context of forest disturbances, as those features were found to be particularly important for determining the agent of disturbance in our analysis. This result highlights the importance of incorporating ecological knowledge into the design of remote sensing approaches, given that the importance of spatial and landscape features for characterizing disturbances is well established in the ecological literature (Sommerfeld et al., 2018; Turner & Gardner, 2015). We here also provide a conceptual framework of how large-scale reference data for disturbance mapping can be gathered. First, we show that visual analysis of existing forest disturbance maps together with existing non-spatial databases and online search tools for newspaper and scientific reports provides a valuable strategy to attribute disturbances to natural disturbances, as has also been shown for Russia recently (Shikhov et al., 2020). While ground-truthing still is the gold standard for assessing the quality of remotely sensed products, it remains impossible at the continental scale, and would necessarily be limited to recent disturbance events. The approach presented here might thus serve as a powerful and operational middle-ground to satisfy the increasing need for spatially explicit assessments of forest disturbances agents. Also, we successfully demonstrate a novel approach for dealing with true absences in reference data by adapting an approach commonly used in species distribution modeling. Yet, we acknowledge that we here test our approach only for two albeit the two most important agents of disturbance in Europe. Further research should thus extent our approach to identify also other agents, most importantly biotic disturbances (Senf et al., 2017). Yet, while there are several databases on wind and fire disturbances in Europe (e.g., FORWIND, EFFIS), similar databases are lacking for biotic disturbances, hampering the collection of reliable reference data.

Despite the novelties of our study there are several methodological limitations that need to be considered when interpreting our results. First, the year in which a disturbance is detected from satellite data might be later than the actual occurrence of the storm or fire event. This happens in particular when storms or fires occur late in the year (after September), leading to an attribution of the event to the following year. This was, for example, the case for storm Lothar, which took place in December of 1999 but shows up in our analysis as peak in storm-related disturbances in 2000. Second, our map does not allow for unbiased spatial analyses by disturbance agent (e.g., patch size distributions), because we used patch size and form as predictor for attributing storm- and fire-related disturbances. Third, many storm-related disturbances in Europe are small, affecting only single trees or groups of trees (Mitchell, 2013). As our analysis is based on a disturbance map with a minimum mapping unit of 0.18 ha, we likely miss many small-scale storm-related disturbances in our analysis. Fourth, we note that our modeling approach is strongly dependent on any selection bias underlying the occurrence information used (Phillips et al., 2009). For example, it cannot be ruled out that during visual interpretation larger patches were preferentially selected as occurrences compared to the overall patch size distribution of all storm- and fire-related disturbances. Hence, there might be a bias in the model that cannot be quantified without additional spatially explicit and independent reference data. Finally, all maps produced from remote sensing data have errors, and estimating area from maps is thus problematic (Olofsson et al., 2013; Palahí et al., 2021). Consequently, we here focus on prevalences, and estimate absolute areas by combining prevalences with an existing sample-based estimator of forest disturbance rates (Senf et al., 2021). This combines the strengths of both approaches and yields an estimate of agent-based disturbance areas with well-quantified uncertainties. Yet, due to the conservative nature of the maps produced in this study, the true rates and areas are likely to be higher. Future users of our data should keep the limitation of map-based area estimates in mind when reporting absolute storm- and fire-related disturbance area, and best use sample-based approaches, as demonstrated in this study.

We conclude by highlighting several important implications for the management of Europe's forests and putting our results in the context of global forest dynamics. First, we here provide evidence that abiotic disturbances are important drivers of regional forest dynamics in Europe. It is thus important for managers to acknowledge the role of natural disturbances in management concepts (Seidl, 2014). Doing this requires a fundamental understanding of the role of natural disturbances (Mori, 2011), which we here contribute to by delivering a first quantitative and spatially explicit assessment of the importance of abiotic disturbances for Europe's forest dynamics. Natural abiotic disturbances should be considered in the long-term planning of forest resources, planning sustainable harvest levels in accordance with the local prevalence of abiotic disturbances. This is especially true for storm-related disturbances, which are increasing in importance in parts of Europe and might thus require compensatory measures by managers. Second, we highlight the importance of storm-related forest disturbance for global forest dynamics. Fire has been well recognized as globally important disturbance agent and much research has been put into modeling global patterns and impacts of fires (Lasslop et al., 2020). Understanding and modeling global patterns and impacts of storm-related disturbances has been less in the focus of the global modeling community to date. As storm-related disturbances are of global relevance (Sommerfeld et al., 2018) and our research suggests similar importance than fire-related disturbances in Europe, we call for further research to improve the mapping and modeling of storm-related disturbances globally.

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AUTHOR CONTRIBUTIONS

CS designed the research, collected all data, performed all analyses and wrote the manuscript. RS contributed to the development of the idea and revised the manuscript.

DATA AVAILABILITY STATEMENT

The disturbance maps are available at https://zenodo.org/record/4570157#.YFByJC337OQ (version 1.0.0). The reference data and code of the analysis are available at https://github.com/corneliussenf/AgentAttributionEurope with a permanent version stored at https://doi.org/10.5281/zenodo.4607164. The final classification maps are available at https://zenodo.org/record/4607230#.YFB5Qy337OQ.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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