Received: 23 November 2023 | Revised: 7 February 2024 | Accepted: 19 February 2024

DOI: 10.1111/gcb.17242

RESEARCH ARTICLE

Global Change Biology WILEY

Ecosystem services at risk from disturbance in Europe's forests

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Funding information
H2020 European Research Council, Grant/Award Number: 101001905; Alexander von Humboldt-Stiftung

Abstract

Global change impacts on disturbances can strongly compromise the capacity of forests to provide ecosystem services to society. In addition, many ecosystem services in Europe are simultaneously provided by forests, emphasizing the importance of multifunctionality in forest ecosystem assessments. To address disturbances in forest ecosystem policies and management, spatially explicit risk analyses that consider multiple disturbances and ecosystem services are needed. However, we do not yet know which ecosystem services are most at risk from disturbances in Europe, where the respective risk hotspots are, nor which of the main disturbance agents are most detrimental to the provisioning of multiple ecosystem services from Europe's forests. Here, we quantify the risk of losing important ecosystem services (timber supply, carbon storage, soil erosion control and outdoor recreation) to forest disturbances (windthrows, bark beetle outbreaks and wildfires) in Europe on a continental scale. We find that up to 12% of Europe's ecosystem service supply is at risk from current disturbances. Soil erosion control is the ecosystem service at the highest risk, and windthrow is the disturbance agent posing the highest risk. Disturbances challenge forest multifunctionality by threatening multiple ecosystem services simultaneously on 19.8 Mha (9.7%) of Europe's forests. Our results highlight priority areas for risk management aiming to safeguard the sustainable provisioning of forest ecosystem services.

KEYWORDS
bark beetle attacks, exposed values, forest multifunctionality, hazard magnitude, hotspots, lack of adaptive capacity, susceptibility, vulnerability, wildfires, windthrows

1 | INTRODUCTION

In Europe, more than 100 million people depend on forests for subsistence and income (European Environmental Agency, 2022). However, the capacity of Europe's forests to provide essential ecosystem services (Lecina-Diaz et al., 2021; Patacca et al., 2022; Seidl, Schelhaas, et al., 2014) is being compromised by disturbances, such as windthrows, bark beetle infestations and wildfires, which have increased strongly over past decades (Ellis et al., 2022; Grünig et al., 2022; Kautz et al., 2017; Seidl et al., 2017). For example, 13.8% of the mean annual timber harvested in the last decades was unplanned harvest directly related to disturbances (Patacca et al., 2022), with a strong negative impact on the timber-based forest economy (Knoke, 2021). Disturbances also reduce carbon storage in Europe's forests (Thom & Seidl, 2016) and can offset efforts of management to increase the forest carbon sink (Seidl, Schelhaas, et al., 2014). Moreover, soil erosion after wildfires is 3–4 times greater than under pre-fire conditions in Europe's forests (Vieira et al., 2023). In addition, forest recreational value decreases after disturbances (Pereira et al., 2021; Sheppard & Picard, 2006), because of aesthetic and scenic losses or safety-related trail closures (Flint et al., 2009). Importantly, forests in Europe provide many ecosystem services simultaneously (Felipe-Lucia et al., 2018; van der Plas et al., 2018). Multifunctionality is an important cornerstone of European forest management (Forest Europe, 2020; Neyret et al., 2023), being at the core of the New EU Forest Strategy for 2030 (European Parliament, 2021). Yet, it remains unclear if and how disturbances impair forest multifunctionality. As forest disturbances are expected to increase in the future (Grünig et al., 2022; Schelhaas et al., 2010), comprehensively addressing disturbance risks to multiple forest ecosystem services is one of the key challenges for current policy and management.

New risk analyses have recently emerged to quantify the impacts of forest disturbances on ecosystem services. Following the Intergovernmental Panel on Climate Change (IPCC, 2022), risk arises from the interaction among three components: exposed values, hazard magnitude, and vulnerability (with the latter resulting from susceptibility and lack of adaptive capacity) (Lecina-Diaz et al., 2020). In the context of forest disturbances, the advantage of this approach is that it explicitly considers spatial variability in these three components. For instance, in the case of exposed values, erosion control is more relevant in steep terrain, while recreational services might be particularly relevant in close proximity to large metropolitan areas. For hazard magnitude, wildfires largely affect the Mediterranean, while high wind speeds occur predominately in Western Europe close to the coast. For vulnerability, tall trees in Central Europe are more susceptible to windthrow than shorter trees in Fennoscandia. In other words, risk analysis explicitly acknowledges that risk is not merely a factor of disturbance occurrence (Ellis et al., 2022; Venäläinen et al., 2020), and that varying impacts of disturbances on ecosystem services need to be considered to quantify disturbance risk.

Effective risk management requires careful consideration and quantification of each of these individual risk components. Disaggregating risk into its components facilitates our understanding of the problem (e.g., by identifying the factors making forests more or less susceptible). This makes it easier to communicate and thus increases policy and management efficiency. Given that resources for risk management are usually limited, risk approaches facilitate evidence-based identification of high priority areas for managing risks. However, analyzing risk across multiple disturbance agents, a range of different ecosystem services, and all relevant risk components remains challenging. Previous studies have equated risk with the probability of disturbance (Ellis et al., 2022; Venäläinen et al., 2020), or only included some but not all risk components identified by the IPCC [e.g., vulnerability (Forzieri et al., 2021; Suvanto et al., 2019) and susceptibility (Nardi et al., 2023; Stritih, Senf, et al., 2021)]. Others have not accounted for ecosystem services explicitly (Baetens, 2022; Schelhaas et al., 2010), or focused only on a specific region (Charnley et al., 2020; Lecina-Diaz et al., 2021; Stritih, Bebi, et al., 2021) or biome (Machado Nunes Romeiro et al., 2022; Venäläinen et al., 2020). Consequently, we do not yet know which ecosystem services are most at risk from disturbances in Europe, where the respective risk hotspots are, nor which of the main disturbance agents are most detrimental to the provisioning of multiple ecosystem services from Europe's forests.

Here, we aimed to quantify the risk to four of Europe's most important forest ecosystem services (timber stock as an indicator for the potential timber supply, carbon stock as an indicator of climate change mitigation, soil erosion control as an important regulating service, and outdoor recreation as an important cultural service) from the three most important forest disturbances in Europe (windthrows, bark beetle outbreaks by the European spruce bark beetle *Ips typographus* L., and wildfires). Specifically, we addressed the following questions: (1) which of the ecosystem services investigated is most at risk? (2) Which of the three disturbances poses the highest risk to ecosystem services supply? (3) Where are the hotspots of disturbance risk in Europe and to what extent do they threaten forest multifunctionality? We addressed these questions by quantifying the risk components (exposed values, hazard magnitude, susceptibility and lack of adaptive capacity) across 200 Mha of Europe's forests. To do so, we curated information from a variety of spatial databases on ecosystem service supply, disturbance probabilities, ecological factors related to forest and landscape characteristics, as well as forest recovery capacity. We synthesized these data using a conceptual disturbance risk framework (Lecina-Diaz et al., 2020), calculating risk individually for each disturbance agent and ecosystem service (spatial grain: 25 km). To identify the ecosystem service most at risk, we aggregated risk across all three disturbance agents and calculated the percentage at risk relative to the overall supply (i.e., exposed value) for each service. Likewise, to identify the most detrimental disturbance agent, we calculated the relative risk to each ecosystem service from each agent. We subsequently identified risk hotspots (80th percentile of continental-scale risk or higher) and quantified the threat to multifunctionality by investigating the co-occurrence of risk hotspots for at least three ecosystem services.

2 | MATERIALS AND METHODS

2.1 | Risk framework

To quantify the risk of losing ecosystem services from forest disturbances, we applied a recently developed state-of-the-art risk framework (Lecina-Diaz et al., 2020, 2021), which includes all risk components recognized by the IPCC (2022), and which considers what happens before, during and after a disturbance (Lecina-Diaz et al., 2020). Risk is defined as follows:

$$\text{Risk} = E \cdot \text{HM}^{\text{S}} \cdot \text{LAC}, \quad (1)$$

where E refers to exposed values, HM is the hazard magnitude, S is susceptibility, and LAC is lack of adaptive capacity. Exposed values (E) are the ecosystem services that could be lost by a disturbance, describing the state of the system before a disturbance hits. Hazard magnitude

(HM) quantifies the probability of disturbance occurrence. Susceptibility (S) is defined by forest characteristics modulating the immediate effects of a disturbance, such as forest structure, tree age, and so forth. Our approach acknowledges the non-linear dynamics of forest systems (Messier et al., 2016) in the interaction between hazard magnitude and susceptibility, with the loss of services increasing to the power of susceptibility with a given probability of occurrence. We used a power function because it ensures that non-linear impacts, which are common in forest ecosystems subject to disturbances, can be easily accommodated. Hazard magnitude and susceptibility thus together describe the immediate impact of a disturbance on the system. Finally, the ability to recover after a disturbance is an important component of risk, which is characterized by a systems' (lack of) adaptive capacity (LAC). For more details on the conceptual approach we refer to Lecina-Diaz et al. (2020).

2.2 | Spatial data

In our analysis of exposed values, we considered four ecosystem services from the main groups of provisioning, regulating and cultural services: (i) timber supply, (ii) carbon storage, (iii) soil erosion control and (iv) outdoor recreation. Each service was characterized by one prominent indicator representing the exposed value in the context of disturbance risk. For timber supply, we focused on timber stocks ($m^3 ha^{-1}$), defined as the timber volume per hectare, and derived by Moreno et al. (2017) by combining inventory data with remote sensing information. For carbon storage, we analyzed forest carbon stocks ($t ha^{-1}$) (Moreno et al., 2017) defined as tons of live tree carbon per hectare (including stem, branches, foliage, coarse and fine roots), and similarly derived by Moreno et al. (2017) from also combining inventory and remote sensing data. Soil erosion control ($t ha^{-1} year^{-1}$) (Maes, 2010) was quantified via an indicator of avoided soil erosion, measuring how much soil is retained by forests using the difference between soil erosion in presence of forests and soil erosion in absence of forests, based on the RUSLE model (Panagos et al., 2014; Panagos, Borrelli, & Meusburger, 2015; Panagos, Borrelli, Meusburger, Alewell, et al., 2015). The cultural service of outdoor recreation (potential daily visits km^{-2}) was taken from Mapping and Assessment of Ecosystem Services 2010 (in particular, INCA; European Commission [Statistical Office of the European Union], 2020) and derived via an analysis of the recreation opportunity spectrum (Vallecillo et al., 2019).We subsequently annualized these values and weighted them by the percentage of forest in each grid cell.

For hazard magnitude we calculated the annual probability of disturbance occurrence. For windthrows, previous analyses showed that moderate to severe disturbance occurs for wind speeds of 30 $m s^{-1}$ or higher (Gardiner et al., 2010). We therefore calculated the probability of wind >30 $m s^{-1}$ occurring, using the windstorm footprints from the Copernicus Climate Change Service (C3S)—Climate Data Store (CDS) (Copernicus Climate Change Service & Climate Data Store, 2022). We fitted the maximum annual wind speed (1981–2018) of each grid cell with a generalized extreme value distribution using the L-moments method as implemented in the 'extRemes' R package (Gilleland & Katz, 2016). From the fitted distributions, we extracted the annual probability of wind speeds exceeding 30 $m s^{-1}$. For bark beetle outbreaks, we used an existing probability map of bark beetle disturbance in Norway spruce [*Picea abies* (L.) Karst.] stands under historical temperature conditions (1979–1990), derived from process-based modelling of bark beetle outbreaks and scaled to the continental level by means of meta-modelling (Hlásny, König, et al., 2021). For wildfires, we used the Fire Weather Index (FWI) maps from the C3S—CDS (Copernicus Climate Change Service & Climate Data Store, 2020), specifically using the daily FWI for the period 1990–2005. We calculated the annual probability of FWI > 24, because values above this threshold have been shown to result in crown fires and complete forest loss (Palheiro et al., 2006; Tedim et al., 2018).

For susceptibility, different ecological indicators at the stand and landscape level modulate the immediate effects of different disturbance agents. For windthrows, trees uproot when wind loading exceeds the resistance of the stem and root system (Seidl, Rammer, & Blennow, 2014). This resistance depends on tree height, spacing, and crown characteristics, and is also influenced by a tree's immediate neighbourhood (e.g., edge tree vs. tree within a stand) (Saad et al., 2017). In general, coniferous species are more susceptible to windthrows than broadleaved ones (Schelhaas et al., 2010). Topographical factors and soil characteristics also affect windthrow susceptibility (Stadelmann et al., 2014; Stritih, Senf, et al., 2021). The windthrow susceptibility indicators used were tree height (m), tree age (years) (Moreno et al., 2017), forest biomass ($t ha^{-1}$) (Avitabile et al., 2020), forest continuity (%) (Copernicus, 2012), percentage of broadleaves (Brus et al., 2012), Topographic Position Index (calculated from a Digital Elevation Model (European Environmental Agency, nd-a), and soil depth available to roots (cm) (European Commission, 2020; Panagos et al., 2012). For bark beetle outbreaks, we focused on the most important bark beetle species in Europe, *Ips typographus*. This species requires mature Norway spruce trees as hosts and generally thrives in continuous and homogeneous forests dominated by its host species (Jaime et al., 2022). As susceptibility indicators we used Norway spruce growing stock ($m^3 ha^{-1}$) (Hlásny, König, et al., 2021), tree age (Moreno et al., 2017), forest continuity (%) (Copernicus, 2012), percentage of broadleaves (the more broadleaves mean fewer host trees and thus also lower susceptibility) (Brus et al., 2012), and soil depth available to roots (cm) (European Commission, 2020; Panagos et al., 2012). For wildfires, fuel load and forest structure increase wildfire susceptibility (Alvarez et al., 2012; Lecina-Diaz et al., 2014), and steeper slopes are associated with higher fire severity and spread (Lecina-Diaz et al., 2014). Thus, the wildfire susceptibility indicators included were forest biomass ($t ha^{-1}$) (Avitabile et al., 2020), branch and foliage biomass ($t ha^{-1}$) (Moreno et al., 2017), tree density (trees ha^{-1}) (Moreno et al., 2017), and Anderson fuel models (Anderson, 1982) as adapted to European landscapes by the European Commission (2017). To characterize forest structure, tree age (years) (Moreno et al., 2017) and height (m) (Moreno et al., 2017) were included, as was slope (°) (European Environmental Agency, 2022) to characterize fire spread and severity (Figure S1).

For lack of adaptive capacity, post-disturbance forest recovery is the most frequently used indicator (Senf & Seidl, 2022; Tepley et al., 2017). We used post-disturbance recovery interval derived from satellite data (Senf & Seidl, 2022) and defined as the average time until a disturbed area will recover to pre-disturbance canopy cover in the period 1986 to 2018. In addition to the natural adaptive capacity of forests to disturbance, this indicator also implicitly considers aspects of human adaptive capacity, as disturbed areas are planted and tended in some parts of Europe. The recovery indicator derived from satellite data thus integrates human and natural processes. For bark beetle outbreaks, we removed the non-Spruce areas (Brus et al., 2012).

2.3 | Data analyses and risk quantification

We scaled the above-mentioned indicators (Figure S1) to 25 × 25 km resolution using either the average (e.g., mean tree age) or the percentage value within each 25 × 25 km grid cell (e.g., percent of broadleaves). Subsequently, we standardized the indicators of susceptibility and post-disturbance recovery for lack of adaptive capacity using min-max normalization:

$$\mathrm{std}_x = x - \min(x) / (\max(x) - \min(x)), \tag{2}$$

where x is the value of the indicator.

We also calculated 1 – std_x, where std_x is the indicator standardized value (range from 0 to 1), when the direction of the indicator was negatively related to susceptibility (e.g., more soil depth available to roots reduces the susceptibility to windthrows). We used indicator weights to combine standardized indicators of susceptibility. Indicator weights can reflect relative importance, statistical additionality or stakeholder preference. Given that we in a previous analysis found that different weight formulations had only a minor effect on the outcome of our risk assessment approach (Lecina-Diaz et al., 2021), here we used statistical weights. Specifically, a weight was assigned to each indicator depending on its statistical importance and additionality extracted from principal component analyses (Lecina-Diaz et al., 2021) (Table S1). Subsequently, the weighted indicators were aggregated to calculate Susceptibility (S) as follows:

$$S = \sum_{i=1}^{n} \left(w_i \cdot \mathrm{std}x_i \right), \tag{3}$$

where S is the sum of the products of each indicator's standardized value ($\mathrm{std}x_i$) and its corresponding weight (w_i). This generated a susceptibility map for each disturbance agent. Since the relationship between hazard magnitude and immediate loss of values that define susceptibility is not linear (i.e., Immediate loss of values = HM^S, see Lecina-Diaz et al., 2020), we assumed that a hazard magnitude of 50% corresponds to a complete loss of values (100%), and susceptibility was then rescaled to a range from 1 to 1.18. Following Equation (1), we raised hazard magnitude to the power of susceptibility, and values were truncated at a maximum loss of 100%. We subsequently multiplied the result by the lack of adaptive capacity and exposed values, obtaining a risk map for each ecosystem service and disturbance, representing the annualized value at risk for every 25 km grid cell.

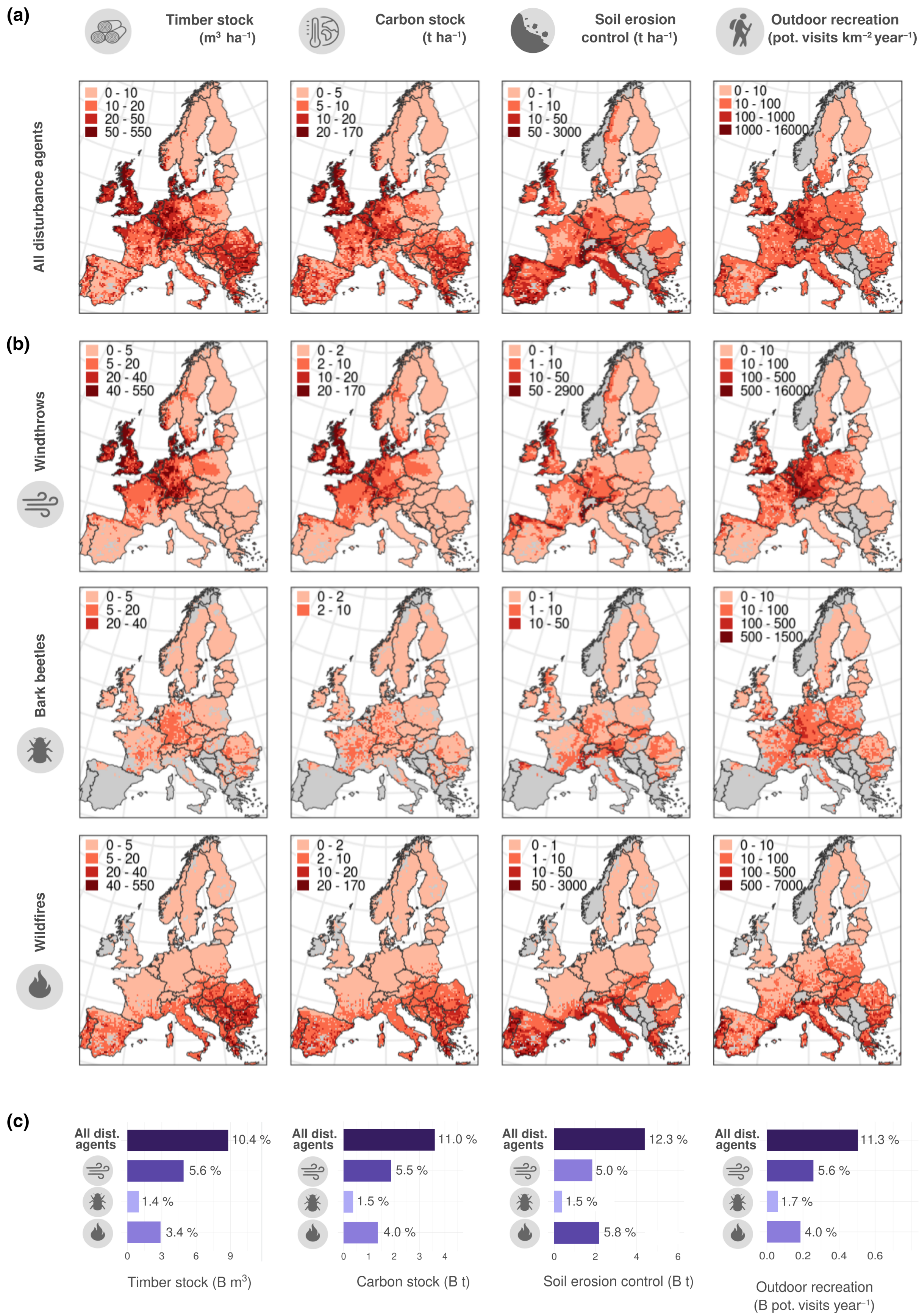
To quantify the overall ecosystem services at risk in Europe's forests, we summed risk across the three disturbance agents. To identify the ecosystem services most at risk, we calculated the percentage at risk relative to the overall supply (i.e., exposed values) for each service. To identify the most detrimental disturbance agent, we calculated the relative risk to each ecosystem service from each agent. To identify risk hotspots, we mapped areas with risk values at or above the 80th percentile (Lecina-Diaz et al., 2018). To analyse the specific characteristics of risk hotspots, we contrasted them with non-hotspot areas with regard to mean annual temperature (°C), mean annual precipitation (mm) (Karger et al., 2017, 2018), mean elevation (m a.s.l.), the share of broadleaved species (%) and tree species richness (Brus et al., 2012). Finally, to analyse the potential risk to multifunctionality we assessed the co-occurrence of risk hotspots for at least three ecosystem services.

3 | RESULTS

3.1 | Ecosystem services at risk from disturbance

Soil erosion control is the ecosystem service at the highest risk from natural disturbances in Europe (12.3% of the overall ecosystem service supply), followed by outdoor recreation (11.3%), carbon stock (11.0%) and timber stock (10.4%) (Figure 1a,c). Specifically, 4.4 B t of soil, 0.5 B of potential recreational visits year^{-1}, 3.6 B t of carbon, and 8.8 B m^3 of timber are at risk from the combined impacts of windthrow, wildfire and bark beetle outbreaks. The areas at highest risk of losing timber and carbon stocks are located in Central and Western Europe, while risk to soil erosion control is highest in Southern Europe and major mountain areas such as the Alps and Cairngorms (Figure 1a). Risk to outdoor recreation is more evenly

FIGURE 1 Ecosystem services at risk from disturbance in Europe's forests. (a) Maps of the ecosystem services: timber stock ($m^3\,ha^{-1}$), carbon stock ($t\,ha^{-1}$), soil erosion control ($t\,ha^{-1}$) and outdoor recreation (potential visits $km^{-2}\,year^{-1}$) at risk from all disturbance agents considered here. (b) Maps of the ecosystem services (timber stock [$m^3\,ha^{-1}$], carbon stock [$t\,ha^{-1}$], soil erosion control [$t\,ha^{-1}$] and outdoor recreation [potential visits $km^{-2}\,year^{-1}$, from left to right] at risk from windthrows, bark beetles and wildfires [from top to bottom]). Grey colour in the maps shows areas without data, except for bark beetle where they show areas without Norway spruce. (c) Total amount of the ecosystem service at risk in Europe's forests from all disturbance agents considered as well as from each disturbance agent individually, with greater risks highlighted with darker colours. Depicted in (c) are the percentages of overall continental-scale ecosystem service value that are at risk from each disturbance agent (ecosystem service at risk divided by the total ecosystem service value). Map lines delineate study areas and do not necessarily depict accepted national boundaries.


(a)
Timber stock (m³ ha⁻¹)
Carbon stock (t ha⁻¹)
Soil erosion control (t ha⁻¹)
Outdoor recreation (pot. visits km⁻² year⁻¹)
All disturbance agents
0 - 10
10 - 20
20 - 50
50 - 550
0 - 5
5 - 10
10 - 20
20 - 170
0 - 1
1 - 10
10 - 50
50 - 3000
0 - 10
10 - 100
100 - 1000
1000 - 16000
(b)
Windthrows
0 - 5
5 - 20
20 - 40
40 - 550
0 - 2
2 - 10
10 - 20
20 - 170
0 - 1
1 - 10
10 - 50
50 - 2900
0 - 10
10 - 100
100 - 500
500 - 16000
Bark beetles
0 - 5
5 - 20
20 - 40
0 - 2
2 - 10
0 - 1
1 - 10
10 - 50
0 - 10
10 - 100
100 - 500
500 - 1500
Wildfires
0 - 5
5 - 20
20 - 40
40 - 550
0 - 2
2 - 10
10 - 20
20 - 170
0 - 1
1 - 10
10 - 50
50 - 3000
0 - 10
10 - 100
100 - 500
500 - 7000
(c)
All dist. agents
10.4 %
5.6 %
1.4 %
3.4 %
0 3 6 9
Timber stock (B m³)
All dist. agents
11.0 %
5.5 %
1.5 %
4.0 %
0 1 2 3 4
Carbon stock (B t)
All dist. agents
12.3 %
5.0 %
1.5 %
5.8 %
0 2 4 6
Soil erosion control (B t)
All dist. agents
11.3 %
5.6 %
1.7 %
4.0 %
0.0 0.2 0.4 0.6
Outdoor recreation (B pot. visits year⁻¹)

distributed across Europe, with high risk areas in densely populated regions of Central and Western Europe. All four ecosystem services were at low risk in the forests of Fennoscandia (Figure 1a).

Forest area under high disturbance risk (>80th percentile of risk values) was greatest for soil erosion control, with 40.1 Mha (19.8% of the forest area) at high risk for losing this provisioning service. Carbon stock had the lowest area at high risk with 29.9 Mha (14.7%) (Table S2). Areas of high disturbance risk had generally warmer mean annual temperatures than non-hotspot areas (+1.8°C on average) and experienced higher levels of mean annual precipitation (+195 mm) (Figure 2; Table S3). Hotspots of disturbance risk also had a higher share of broadleaved tree species (+11%) and higher tree species richness (+1.1 species). For soil erosion control, risk hotspots were at higher elevations than areas of lower risk (+408 m) (Figure 2; Table S3).

3.2 | Risk from different disturbance agents

Windthrows pose the highest risk to ecosystem services supply among the three disturbance agents considered here (threatening between 5.0% and 5.6% of all ecosystem services, depending on the service), followed by wildfires (from 3.4% to 5.8%) and bark beetles (from 1.4% to 1.7%) (Figure 1b,c). However, risk varied considerably with disturbance agent and ecosystem service (Figure 1b). Windthrows exert high risk across all ecosystem services in Central and North-Western Europe, where the probability for exceeding wind speed >30 m s^{-1} is high. High-risk areas for bark beetles are mainly located in Central Europe, with outdoor recreation being particularly affected. For wildfires, high risk areas are mainly located in Southern Europe, where wildfires occur with higher frequency than in other parts of Europe (Figure S2). Overall, the spatial variation of risk among disturbance agents is greater than the spatial variation of risk among ecosystem services.

3.3 | Risk to ecosystem multifunctionality

The risk of simultaneously losing multiple ecosystem services to disturbances is considerable, with three or more ecosystem services being at high risk on 19.8 Mha (9.7%) of Europe's forest area. Central and Western Europe had the highest risk of losing forest multifunctionality (Figure 3a). High disturbance risk often co-occurred for timber, carbon and outdoor recreation (13.4 Mha forests, 6.6% of

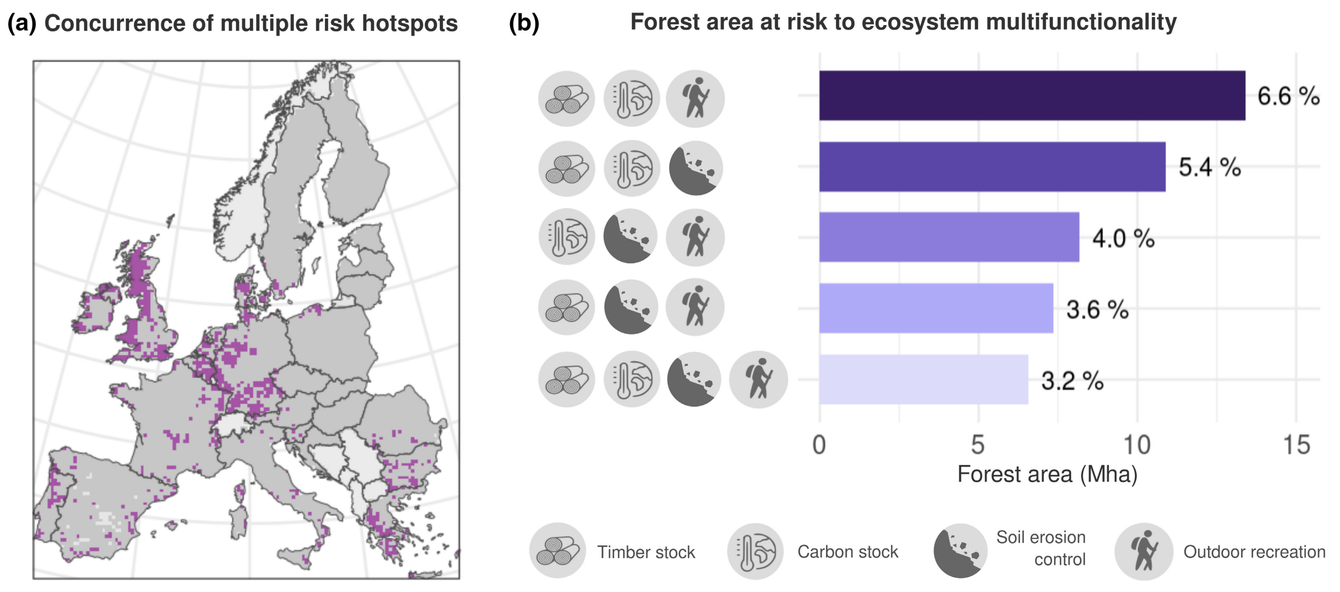
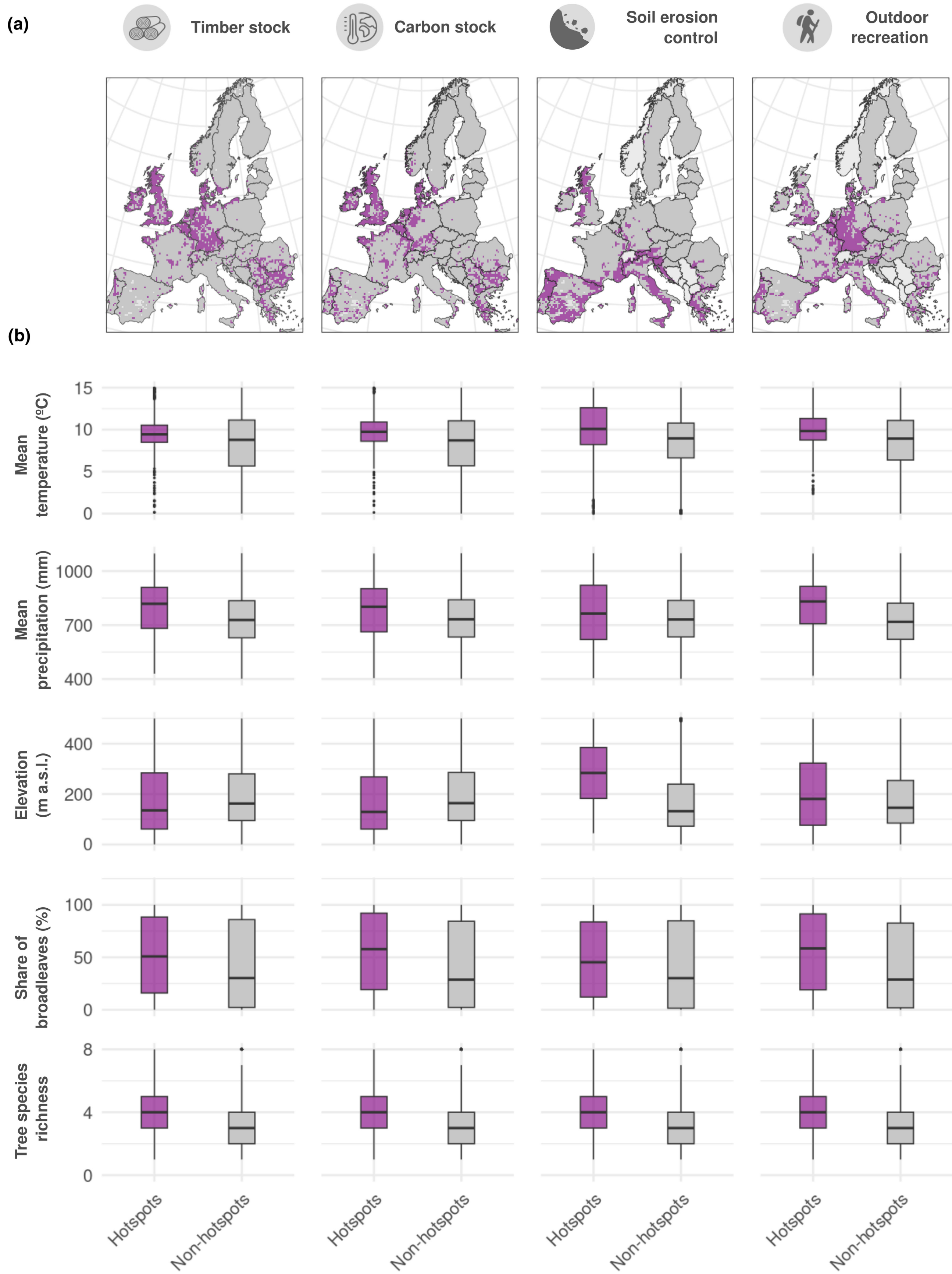


FIGURE 2 The spatial distribution of risk hotspots from disturbances in Europe's forests. (a) Maps of the risk hotspots (>80th percentile of risk values) from the joint effect of windthrows, bark beetles and wildfires for the ecosystem services timber stock, carbon stock, soil erosion control and outdoor recreation. The highlighted areas indicate hotspots of risk, dark grey areas show non-hotspots and light grey areas indicate no-data. (b) Box-plots of context indicators in hotspots and non-hotspots areas: mean temperature (°C), mean precipitation (mm), elevation (m), share of broadleaves (%) and tree species richness. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

FIGURE 3 Areas where forest multifunctionality is at high risk. (a) Map of disturbance risk hotspots (>80th percentile of risk values) for three or more ecosystem services considering all disturbances jointly (windthrows, bark beetles, and wildfires). The highlighted areas indicate locations where the simultaneous provisioning of multiple ecosystem services is at high risk (hotspots), dark grey areas show non-hotspots and light grey areas indicate no-data. (b) Forest area where ecosystem multifunctionality is at risk depending on the combination of ecosystem services considered, with greater forest area at risk highlighted with darker colors. The percentages correspond to continental-scale forest area percentage with high risk to multifunctionality (total forest area at risk divided by the total area of forest in Europe). Map lines delineate study areas and do not necessarily depict accepted national boundaries.



(a)
Timber stock
Carbon stock
Soil erosion control
Outdoor recreation
(b)
Mean temperature (ºC)
15
10
5
0
Mean precipitation (mm)
1000
700
400
Elevation (m a.s.l.)
400
200
0
Share of broadleaves (%)
100
50
0
Tree species richness
8
4
0
Hotspots
Non-hotspots

Europe's forests) (Figure 3b). On 6.6 Mha (3.2%), all four ecosystem services were at high risk from forest disturbances.

4 | DISCUSSION

Forest disturbances are increasing rapidly in Europe (Senf et al., 2021), with the past years constituting the biggest wave of tree mortality in at least 170 years (Senf & Seidl, 2021a). We here showed that disturbances have substantial negative impacts on the ecosystem services that forests supply to society. We found that 10.4%–12.3% of the ecosystem services provided by Europe's forests are at risk from windthrows, bark beetles and wildfires, underlining the considerable challenge that disturbances pose for ecosystem management. We furthermore found that 19.8 Mha of forest are at high risk of losing multiple ecosystem services simultaneously, suggesting that disturbances threaten the multifunctionality of forest ecosystems.

Our results are well in line with previous assessments highlighting negative impacts of forest disturbances on ecosystem services (Seidl, Schelhaas, et al., 2014; Thom & Seidl, 2016). Specifically, recent disturbances in Europe have considerably reduced timber stocks (Hlásny, Zimová, et al., 2021; Nabuurs et al., 2013), caused timber prices to collapse and threatened the livelihoods of forest owners (Hanewinkel et al., 2012; Machado Nunes Romeiro et al., 2022). Also, disturbances can compromise the climate mitigation potential of forests (Seidl, Schelhaas, et al., 2014; Wang et al., 2021) and have been implicated in the carbon sink saturation in Europe's forests (Nabuurs et al., 2013). While most previous studies on disturbance impacts in Europe have focused on timber or carbon, we here showed that soil erosion control and outdoor recreation are at even greater risk from disturbances. A loss of soil erosion control could have severe and long-lasting consequences, as soil formation takes centuries to millennia, and tree growth depends on soil conditions (Lévesque et al., 2016; Wieder et al., 2015). Losing this service could thus lead to a loss in forest cover, which could have detrimental secondary effects on other ecosystem services, particularly in mountain areas where humans depend strongly on the protective effect of forests (Moos et al., 2023). The recreational value of forests and their contribution to human well-being has recently increased during the Covid19 pandemic (Muro et al., 2022; Pichlerová et al., 2023). As the share of humans living in cities continues to grow, the importance of forests as recreational regions will further increase, particularly in areas of high population density such as in Central and Western Europe (Vallecillo et al., 2019) (Figure S2).

Windthrows and wildfires affect roughly the same amount of forest area in Europe (Senf & Seidl, 2021b), yet we found that the effect of wind on important ecosystem services is more detrimental than the effect of wildfire. Our results are in line with previous analyses highlighting that wind is the most important disturbance agent in terms of timber damage in Europe (Patacca et al., 2022). We here show that wind is also the most detrimental disturbance agent for carbon stocks and recreation, while fire is more important than wind in the context of soil erosion. In our analyses, the risk values for bark beetle disturbances are lower than those for windthrow and fires. This is because we calculated annualized risk values, which do not consider the strong temporal autocorrelation of bark beetle outbreaks (Seidl et al., 2017) (i.e., the fact that a regional outbreak usually continues for several years, compounding its effect on regional ecosystem service provisioning).

We found that hotspots of risk have higher temperatures and higher precipitation than other areas. This suggests that continued global warming could further increase disturbance risk to ecosystem services in Europe, which is in line with expectations derived by means of model-based scenario analyses (Mina et al., 2017). Surprisingly, continental-scale risk hotspots had a higher share of broadleaved trees and were more diverse than non-hotspot areas. Under similar hazard levels, mixed and broadleaved forests are less disturbed than coniferous forests (Schelhaas et al., 2010). However, both hazard magnitude and exposed values are considerably lower in Fennoscandia (Figure S2), where forests are dominated by conifers and where tree species richness is comparatively low. Our finding that disturbance risk hotspots are more diverse thus reflects the specific spatial pattern of disturbances in Europe, rather than a causal link between risk and diversity. In the context of risk management, higher species richness in disturbance risk hotspots might also be advantageous, as diverse forest ecosystems tend to be more resilient to disturbances (Messier et al., 2021), increasing their ability to cope with perturbation.

Multifunctionality is a central pillar of forest policy and management in Europe, where forests are frequently expected to simultaneously provide multiple ecosystem services to society (Felipe-Lucia et al., 2018; van der Plas et al., 2018). Previous studies found the highest potential for ecosystem multifunctionality in Northern and Central Europe (Stürck & Verburg, 2017), as well as in mountainous areas compared to lowland areas (Hölting et al., 2019). We found that this potential could be substantially reduced by disturbances, particularly in Central Europe, while risks to multifunctionality are low in Northern Europe. Disturbances particularly threaten the simultaneous provisioning of timber, carbon, and recreation services in our analysis. This is consistent with findings that stand ages between 100 and 185 years reached the highest levels of multifunctionality (Jonsson et al., 2020), yet forests at this age are more prone to wind and bark beetle disturbances (Schelhaas et al., 2010). Areas where disturbances threaten forest multifunctionality should be prioritized for forest management because they offer opportunities to reduce multiple risks simultaneously, thus increasing management effectiveness. Overall, our finding of considerable risk to the simultaneous provisioning of multiple ecosystem services suggest that disturbances challenge the New EU Forest Strategy for 2030 (European Parliament, 2021) objectives by eroding the potential for forest multifunctionality in Europe.

Important limitations need to be considered when interpreting our findings. First, we focused on the current risk from disturbances and its spatial patterns. As disturbance regimes are changing in Europe, our assessment might be conservative and might not reflect projected increases in disturbance frequency or severity. Future work could use simulation modelling to incorporate scenarios of climate and disturbance change into risk assessments. These dynamic risk assessments will also need to consider the potential future changes in ecosystem service supply, which may also evolve dynamically depending on region and future climate (Mina et al., 2017). Second, we here focused on four ecosystem services, disregarding other important services such as water regulation or wildlife habitat provision due to the lack of continental-scale data availability. Including other ecosystem services in the analysis might change our outcomes, since different synergies or trade-offs may arise. Third, we note that some components of the risk framework applied here have better empirical support than others. Future research should focus on improving our understanding of components such as the (lack of) adaptive capacity of social-ecological systems to disturbance. This remains poorly understood and was here approximated by a remotely-sensed indicator of post-disturbance recovery, only implicitly considering differences in social adaptive capacity. Similarly, the effects of disturbances on ecosystem services such as timber and carbon are better understood compared to other ecosystem services. With regard to recreation, for instance, we assumed a negative effect of disturbances on the recreational value of forests based on a number of previous studies (Bawa, 2017; Pereira et al., 2021). Other studies did not find a strong relationship between disturbance severity and recreational value of forests (Kortmann et al., 2021), which underlines that further research on the impacts of disturbances on a range of ecosystem services is needed.

Our study is the first quantitative and spatially explicit multi-hazard multi-service risk assessment for Europe's forests; as such it provides an important basis for improved forest policy and management. Specifically, our findings can be used to identify priority areas for risk management, e.g., where reducing risk can benefit multiple ecosystem services. This is particularly important as risk management resources are limited and evidence-based methods for prioritizing management efforts are needed. Our results highlight that disturbance risk affects large parts of Europe's forests without regard for jurisdictional boundaries, underscoring the need for transnational information sharing, knowledge exchange and coordinated pan-European risk management (Hlásny, König, et al., 2021). A major advantage of our approach is that individual components contributing to risk can be assessed and monitored separately, making the main drivers of risk tangible for policy and management. Risk analysis facilitates the development of risk management strategies by highlighting which factors contribute most strongly to risk, thus identifying opportunities for targeted management interventions. Potential risk management measures include reducing susceptibility, for instance by decreasing forest continuity for wildfires (Alvarez et al., 2012) or decreasing bark beetle host tree cover (Jaime et al., 2022; Nardi et al., 2023). Additional risk management measures increasing adaptive capacity [e.g., through tree planting or assisted migration in areas with low recovery capacity (Messier et al., 2015), or managing the exposed values (Albrich et al., 2018)]. As disturbances continue to increase in Europe, maintaining a continuous and sustainable supply of ecosystem services will be increasingly challenging. Formal risk analysis can support forest policy and management in effectively addressing these risks, in order to safeguard the manifold contributions of forest ecosystems to human well-being.

AUTHOR CONTRIBUTIONS

Judit Lecina-Diaz: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; validation; visualization; writing – original draft. **Cornelius Senf:** Data curation; writing – review and editing. **Marc Grünig:** Data curation; writing – review and editing. **Rupert Seidl:** Conceptualization; investigation; methodology; writing – review and editing.

ACKNOWLEDGEMENTS

We acknowledge Kristin H. Braziunas for helpful comments on the manuscript. J.L.-D. was funded by the Alexander von Humboldt Foundation. R.S. acknowledges funding from the European Research Council under the European Union's Horizon 2020 research and innovation program (Grant Agreement 101001905, FORWARD). Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in zenodo at https://doi.org/10.5281/zenodo.10688003.

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SUPPORTING INFORMATION

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

How to cite this article: Lecina-Diaz, J., Senf, C., Grünig, M., & Seidl, R. (2024). Ecosystem services at risk from disturbance in Europe's forests. *Global Change Biology*, *30*, e17242. https://doi.org/10.1111/gcb.17242