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RESEARCH ARTICLE

Setting aside areas for conservation does not increase disturbances in temperate forests

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Abstract

1. Forest disturbances are increasing in many parts of the globe, posing a considerable challenge for forest management. Simultaneously, setting aside forests for conservation is considered an important approach to halt ongoing biodiversity loss. While the potential for increasing disturbances is often invoked as an argument against creating forest reserves within the matrix of managed forest landscapes, quantitative evidence for the impact of conservation areas on forest disturbance regimes remains scarce.
2. Here, we contrasted forest disturbance regimes in actively managed and set-aside areas throughout Germany. We made use of a network of strict forest reserves protected for at least 35 years (i.e. set-aside areas) and identified comparable managed forests by controlling for differences in species composition, climate and topography ($n=314$ pairs of managed and set-aside areas with 20 ha in size). A remote-sensing-based forest disturbance map with annual disturbance records for the years 1986 to 2020 was used to quantify disturbance regimes. Within the context of the coupled human and natural disturbance regimes of Central Europe, we here focused on canopy openings initiated by naturally occurring agents like wind-throw, drought and bark beetle infestations. Our main objective was to identify the impact of setting aside forests on disturbance rate, frequency, patch density, patch size and severity.
3. We found that set-aside areas had, on average, a 22% lower disturbance rate and a 32% lower disturbance severity compared with actively managed forests, with no significant differences detected for disturbance patch size, patch density and frequency. Lower disturbance activity in set-aside areas was particularly pronounced in mixed and broadleaved forest types. The dampening effect of strict forest reserves strengthened in pulse disturbance years, that is years with very high disturbance activity caused by extreme storm or drought events.
4. *Synthesis and applications*: We found no evidence that setting aside forests for biodiversity conservation amplifies disturbances in temperate forests of Central Europe. Conversely, we found that strict forest reserves had lower disturbance activity, particularly in years affected by severe climatic extremes. We conclude

that considerations of disturbance should not limit the incorporation of reserves into landscape management in temperate forests.

KEYWORDS
forest conservation, forest disturbances, forest management, protected areas, remote sensing, strict forest reserves, temperate forests

1 | INTRODUCTION

Disturbances are an integral component of forest ecosystem dynamics (Kulakowski et al., 2020) and make an important contribution to forest ecosystem complexity (Seidl et al., 2011). However, forest disturbance regimes are changing around the globe (McDowell et al., 2020), posing an important challenge for ecosystem management. Central Europe has been a hotspot of disturbance change, with more than a doubling in disturbance rates over the past 35 years (Patacca et al., 2022; Senf et al., 2018), and an unprecedented wave of tree mortality from drought and bark beetles affecting the area since 2018. Climate change is anticipated to further amplify disturbance activity in the coming decades (Seidl et al., 2017). A better understanding of changing disturbance dynamics is a key prerequisite for addressing disturbance change in forest policy and management (Hanewinkel et al., 2011; Seidl, 2014).

Besides changes in disturbance regimes, rapid biodiversity loss is a key concern in science and policy (Richardson et al., 2023). A combination of habitat loss, climate change, pollution and overexploitation of natural resources drives the observed biodiversity decline (Oliver, 2018). The conservation of biodiversity is thus an objective of growing importance also for forest management (Thorn et al., 2018). A key tool of biodiversity conservation is to set-aside areas, that is define conservation areas that are no longer actively managed (Johnson et al., 2017). In this context, the Kunming–Montreal Global Biodiversity frameworks seek to respond to the biodiversity crisis by protecting 30% of the terrestrial land area (UNEP, 2022). Achieving this target requires a considerable increase in areas under protection compared with the current situation.

Set-aside areas are often argued to undermine the efforts to reduce forest disturbance risks on the landscape due to the absence of risk management in these areas (Fettig & Hilszczański, 2015; Stadelmann et al., 2013). No or minimal risk management routines in set-aside areas, for example against bark beetles, can result in higher spread rates of biotic disturbances (Stadelmann et al., 2013) and a spillover of outbreaks to managed forests. However, Valeria et al. (2016) demonstrated that set-aside areas act as sinks rather than sources for bark beetle populations due to the active population control measures in the matrix that surrounds them. Simultaneously, the absence of regular harvesting reduces the amount of stand edges in set-aside areas, making them less prone to wind-throws (Zeng et al., 2009). Furthermore, naturally developing forests often exhibit more heterogeneous canopy structures (Seidel & Ammer, 2023), which are less prone to wind disturbance (Díaz-Yáñez et al., 2017; Mohr et al., 2024; Wohlgemuth et al., 2022). Based on the available evidence, it thus remains unclear whether set-aside areas have higher or lower disturbance activity compared with actively managed forests (here defined as forests managed to supply provisioning, regulating and cultural ecosystem services to society).

The main natural agent of disturbance in Central Europe's forests is wind, which accounts for approximately 46% of the total timber volume disturbed (Patacca et al., 2022). Bark beetles are the most important biotic disturbance agents and also the agents increasing most rapidly in past years. The most important bark beetle species in Europe is *Ips typographus* L., which primarily targets Norway spruce [*Picea abies* (L.) Karst] (Jakoby et al., 2019). A few extreme wind events cause large pulses of tree mortality and make a disproportionately large contribution to the overall area disturbed (Senf & Seidl, 2021b). Likewise, bark beetle disturbances occur in waves, triggered by abiotic extremes such as wind and drought. In the following, we will distinguish between years with peak disturbance activity as 'pulse years' and years with low disturbance activity as 'background years'. This distinction is important in the context of management, as some evidence suggests that active disturbance management measures are less effective in pulse years (Mathes et al., 2023). However, forest management can also have a pre-empting effect on disturbances by reducing the amount of vulnerable stands (Frelich et al., 2018). It is thus of particular relevance to understand how setting aside areas for conservation affects disturbance activity in pulse disturbance years, especially since the climatic extremes that trigger them will likely increase in the future (Seidl et al., 2017).

Disturbance regimes change along multiple dimensions, with disturbance rate, patch size, patch density, frequency and severity responding to global change simultaneously (Turner & Seidl, 2023). Addressing these multiple dimensions requires a look beyond the stand scale (e.g. Jactel et al., 2009), as disturbance regimes are landscape-scale phenomena (Turner et al., 2001). Remote sensing is a powerful tool to consistently quantify disturbance regimes at the landscape scale (Senf, 2022). Recent advances in remote sensing provide analysis-ready datasets of forest disturbances across large spatial and temporal scales (Hirschmugl et al., 2017; Senf & Seidl, 2021a), which enable analyses of disturbance regimes

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across forests managed for different objectives (such as set-aside areas for conservation and forests managed to supply ecosystem services).

Here, our objective was to compare the disturbance regime of the years 1986 to 2020 in managed forests and set-aside areas across Germany. Using satellite-derived disturbance information for strict forest reserves and managed forests with comparable topography, forest type and climate, we (i) quantified differences in disturbance rate, patch size, patch density, frequency and severity between managed and set-aside forests and (ii) analysed whether the effects of setting areas aside differed in years with disturbance pulses compared to years with background disturbance activity. We hypothesized that (1) set-aside areas are less disturbed than managed forests due to the absence of planned canopy openings (Seidl & Senf, 2024). The alternative hypothesis is that management successfully reduces disturbance risk and contains disturbance spread, resulting in lower disturbance rates and smaller disturbance patch sizes (Giuggiola et al., 2013). We further hypothesized (2) that set-aside areas have lower disturbance rates than managed forests, particularly in pulse disturbance years (i.e. years with strong wind or drought events) (Díaz-Yáñez et al., 2017; Mohr et al., 2024). Alternatively, forest risk management measures are also able to dampen the impact of extreme disturbance events in managed forests (Stadelmann et al., 2013).

2 | MATERIALS AND METHODS

2.1 | Study area and data

2.1.1 | Study area

We studied disturbance regimes in forest landscapes across Germany, covering a wide gradient in forest types and climate. Germany's forest area (approximately 32% of the total land area) is dominated by Norway spruce, Scots pine (*Pinus sylvestris* L.), European beech and deciduous oak species [*Quercus robur*. L. and *Quercus petrae*a (Mattuschka) Liebl.] (Blickensdörfer et al., 2024). Environmental conditions vary and range from northern lowland plains, across central uplands with mountain ranges up to 1500 m a.s.l., to mountain forests in the south, including the northern front range of the Alps. Climatic conditions range from oceanic in north-western regions to a continental climate, which predominates in the east of Germany (Zöller et al., 2017). After a century-long history of even-aged forest management focused on conifers (mainly Norway spruce and Scots pine) (Spiecker, 2003), the silvicultural paradigm is shifting towards continuous cover management of mixed forests, employing thinning at regular intervals and selection cutting (Juutinen et al., 2022). Overall, 22% of German forests are single-layered, 61% have two canopy layers, and 17% are multi-layered (Riedel et al., 2024). They are predominantly privately owned (48%) and are managed for a variety of ecosystem services under a paradigm of multi-purpose forest management. Only 3.1% of the forest area is conserved in strict forest reserves and national parks (Steinacker et al., 2023).

2.1.2 | Disturbance data

To quantify disturbance regimes, we used the European forest disturbance map (Senf & Seidl, 2021a), which identifies forest disturbances based on Landsat satellite data on an annual basis between 1986 and 2020. The spatial resolution is 30 × 30 m. Disturbance severity is mapped per pixel as the probability of stand-replacing disturbance, with zero indicating no change in the dominant canopy and one indicating the complete removal of the forest canopy (Senf & Seidl, 2021a). We here used a disturbance agent attribution (Senf & Seidl, 2021b) to subset disturbances to those triggered by naturally occurring agents (e.g. wind-throw and bark beetle). Planned canopy openings resulting from forest management were not included in our analyses. We note that the forest disturbance regime in Europe is a coupled human and natural system (Seidl & Senf, 2024), with management frequently responding to disturbances from natural agents, for example via salvage logging (Leverkus et al., 2021). We here considered all disturbances that were triggered by natural agents (i.e. unplanned canopy openings), regardless of post-disturbance management responses.

2.1.3 | Set-aside areas

A set of protected areas set aside for conservation was compiled, consisting of strict forest reserves and core zones of national parks across Germany (Figure 1). The minimum forest area for inclusion was 20 ha. This follows the finding by Urban et al. (1987) that in order to capture disturbance regimes, study areas should exceed disturbed areas by a factor of 50 (median disturbance patch size for Germany: 0.45 ha). The size of set-aside areas under study varies strongly and is skewed towards small reserves (46% of areas <40 ha). Timber harvesting ceased in all areas prior to 1986, that is the first year for which disturbance information is available. Overall, we studied 151 set-aside areas, covering a forest area of 31,483 ha, comprising 148 strict forest reserves, the core zones of Berchtesgaden National Park, Bavarian Forest National Park and a subset of Hainich National Park. The largest protected area included was 12,782 ha (Bavarian Forest National Park). Nearly half of all set-aside areas represent spruce-dominated forests (48% or 15,984 ha), 21% are beech forests (6896 ha), 2% oak forests (669 ha), 0.5% pine forests (185 ha), 9% conifer-dominated mixed forests (2905 ha), 6% broadleaved-dominated mixed forests (1948 ha), 6% mixed forests of broadleaves and conifers (1897 ha) and 8% other forest types (2673 ha). The overarching goal of these set-aside areas is conservation. Consequently, active human interventions are reduced to a minimum and include game management, fire protection and debarking or removal of bark beetle-infested trees (estimated for less than 2% of the area under study).

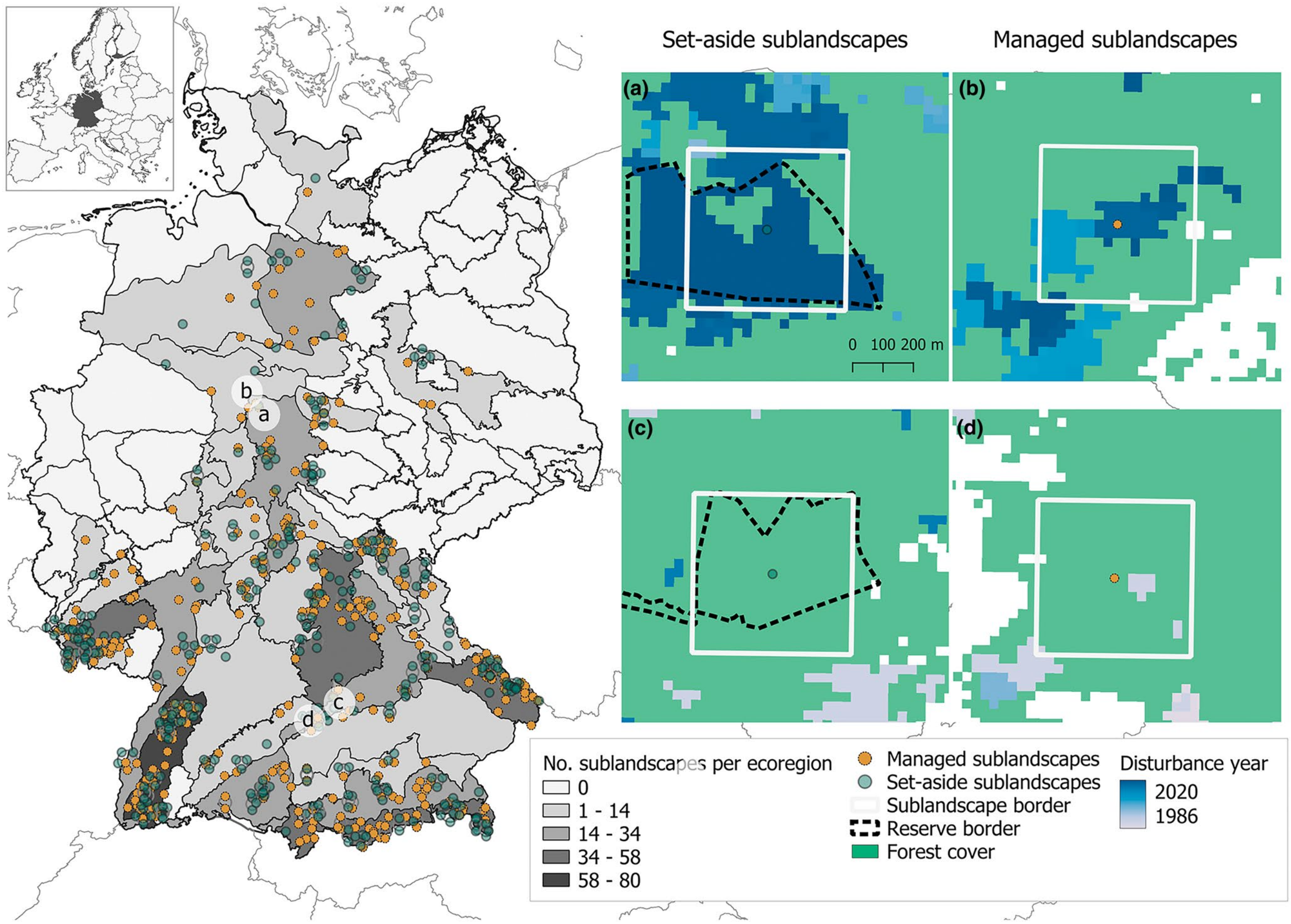

FIGURE 1 Location of the paired sublandscapes in managed forests and set-aside areas across Germany. Different ecoregions are shown in grey. Close-up (a) shows a sublandscape in a set-aside area with a high disturbance rate, (b) is the paired managed sublandscape. Close-up (c) shows an undisturbed sublandscape from a set-aside area, while (d) is the paired managed sublandscape.

2.1.4 | Auxiliary data

We used the European Digital Elevation Model (EU-DEM) by the Copernicus service (25 m resolution) and resampled it to the resolution of the European forest disturbance map to obtain information on elevation, aspect and slope for our study sites. To account for differences in climate and site conditions, we used a fine-grained set of ecoregions for Germany (Thünen-Institut, 2022). Ecoregions were defined as areas having similar geomorphological conditions (bedrock type and terrain formation), climate and land-use history (Gauer et al., 2012). The median ecoregion size was 326,649 ha, and in total, 82 ecoregions were distinguished within Germany (Thünen-Institut, 2022). To obtain tree species information consistently across all study areas, we used a remotely sensed tree species map (10 × 10 m resolution), considering 11 different tree species as well as mixture classes (Blickensdörfer et al., 2024). We aggregated tree species information to 1 ha resolution using a rule-based majority vote (details in Text S1) and resampled the resultant map to the forest disturbance map for further analyses.

2.2 | Analyses

2.2.1 | Sublandscape selection and matching

We identified for each set-aside area a managed forest with comparable environmental conditions, enabling a pairwise comparison of disturbance regimes. First, we randomly drew sublandscapes from set-aside areas. The initial size of the sampled sublandscapes was 15 × 15 pixels of 0.09 ha, that is 20.25 ha, but due to the varying shapes of protected areas, the sampling window was adapted, and the realized sublandscapes varied between 19.2 and 24.6 ha. We allowed for a maximum of 50% overlap of sampled sublandscapes and down-sampled the core areas of national parks and large strict forest reserves so that they did not dominate the analysis due to their large extent. We sampled one sublandscape in the smallest size bin of set-aside areas (20–30 ha) and progressively increased the number of sublandscapes up to a maximum of 10 in the largest protected areas (details in Table S1). We used the subsample.distance function of the spatialEco R package (Evans et al., 2023) for the sublandscape

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selection. In total, we sampled 314 set-aside sublandscapes (6281 ha of forest area) from the 151 protected areas described above.

Subsequently, we identified sublandscapes from managed forests with similar environmental conditions. For this, we assumed that all forests not strictly protected are managed, disregarding potential differences in management intensity. We controlled for environmental variables in selecting suitable pairs of managed forests and set-aside areas. The variables considered were mean elevation, mean slope and north-westernness (representing wind exposure and different solar radiation regimes), the shares of forest types on the landscape, as well as ecoregion (representing similar soil and climate conditions). The main analysis was done based on a 1:1 matching between managed and set-aside areas (Text S1). In total, we analysed 628 sublandscapes, of which 50% were managed and 50% were set aside. However, to consider the variation in managed forests throughout Germany (e.g. with regard to management objectives, management intensity) we repeated the analysis also with a matching scheme in which we compared each selected sublandscape from a set-aside area with multiple managed sublandscapes of similar environmental conditions (1:Many). The results of this additional analysis did not differ substantially from the pairwise comparison and are presented in Table S4.

2.2.2 | Disturbance metrics

For each sublandscape, we extracted five disturbance metrics to characterize the disturbance regime. The metrics included (i) disturbance rate (percent of the sublandscape disturbed annually), (ii) maximum disturbance patch size, that is the single largest disturbance patch within the landscape in the period 1986–2020, (iii) patch density, describing the number of disturbance patches per landscape, (iv) frequency, that is how often the landscape was disturbed in the observation period, and (v) high severity rate. High severity rate describes the percentage of disturbed pixels that are disturbed with a severity ≥0.8. A sensitivity analysis of the high severity threshold revealed robust results also for other values (see Table S5). We provide a detailed description of all disturbance metrics and their interpretation in Table S2. All data processing was performed with the terra package (Hijmans et al., 2023) in R (R Core Team, 2022).

2.2.3 | Statistical analyses

For hypothesis 1—testing for differences between managed forests and set-aside areas—we estimated annual mortality rates using a beta binomial model with a logit link function to account for over-dispersion in the observed counts. The probability of observing a given number of disturbed forest pixels was modelled as a function of treatment (managed and set-aside), with random intercepts for the combination of year and site (paired landscape ID). Furthermore, to investigate the interaction between treatment and forest type, we included the forest types in the model and allowed for an interaction term between treatment and the share of forest types on the landscape. We modelled each response variable as a function of the fixed effect (treatment) and random intercepts for site. For the response variables disturbance frequency and patch density, we fitted truncated Poisson models, for maximum patch size, a lognormal model, and for high severity rate, a beta binomial model with a logit link.

To test hypothesis 2—assessing the effect of set-aside in pulse and background years—we extended the models described above with the classification of the respective years in pulse and background years. We labelled years as pulse disturbance years when the overall disturbed area in Germany exceeded the average area disturbed between 1986 and 2020 by more than 100% (Figure S8). We identified the years 1990, 2000, 2007, 2018, 2019 and 2020 as pulse disturbance years, with all other years considered background years. We estimated model uncertainty by bootstrapping 80% of the input data 100 times to build 100 models estimating the disturbance rate for pulse and background years in managed forests and set-aside areas. We evaluated all models by simulation-based model checks using the glmmTMB package (Brooks et al., 2017).

3 | RESULTS

3.1 | The effect of setting aside forests on the disturbance regime

We found that set-aside areas had a 22% (95% confidence interval: 9%–33%) lower disturbance rate than managed forests (Figure 2). The average disturbance rate of set-aside sublandscapes was 0.06% year^{-1}, while managed sublandscapes were disturbed at a rate of 0.08% year^{-1}. We tested whether this finding was driven by specific ecoregions but found no region-specific patterns (see Figure S7). The 1:Many comparison did not reveal substantially different results than the 1:1 comparison of sublandscapes (see Table S4). Of the 628 sublandscapes analysed, 274 (44%) were disturbed, of which 156 were managed and 118 were set-aside (57% and 43% of the disturbed landscapes, respectively).

The only other disturbance metric that was significantly different was the rate of high severity disturbances, which was 32% (95% confidence interval: 12%–48%) lower in set-aside areas compared with managed forests (36% vs. 45%). All other metrics did not differ significantly, with a similar number of disturbed patches (on average 3.5 vs. 3.2 patches), similar disturbance frequency (on average 1.8 vs. 1.7 disturbances in the observation period) and similar maximum disturbance patch size (on average 1.66 ha vs. 1.72 ha) in managed forests and set-aside areas (see Table S4 for the 1:Many comparison).

The effect of forest management on disturbance rate varied with forest type. Disturbance rates generally increased with increasing share of spruce and mixed coniferous forests on the landscape, and decreased with increasing share of beech and mixed broadleaved

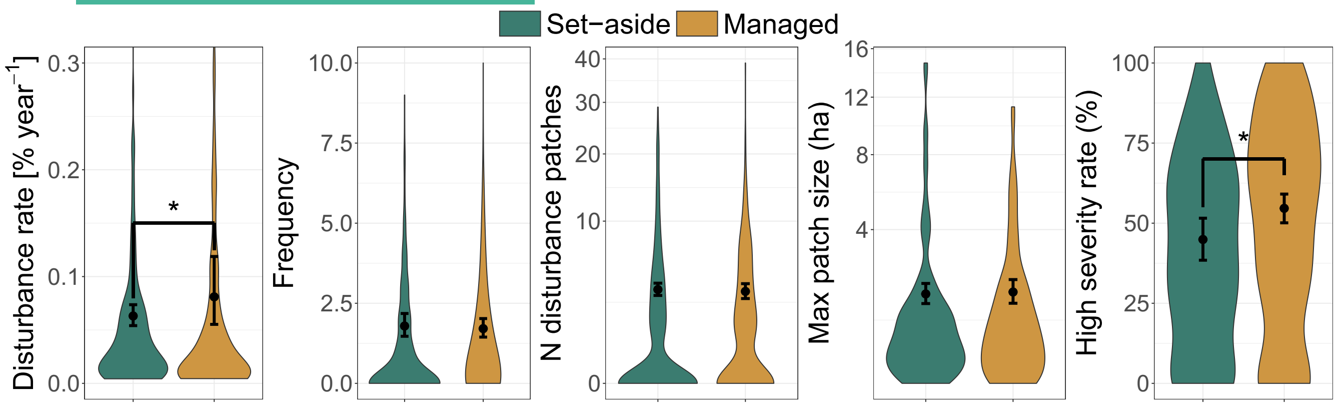

FIGURE 2 Distribution of disturbance metrics for managed and set-aside sublandscapes in Germany. Distributions of the raw data (violins) are combined with the effect size of the respective model estimates (points and whiskers). The point represents the model estimate, and the whiskers represent the 95% confidence interval of the estimate. Asterisks mark significant differences at $\alpha = 0.05$. Note that the y-scale for N disturbance patches and Max patch size is transformed to the square-root scale.

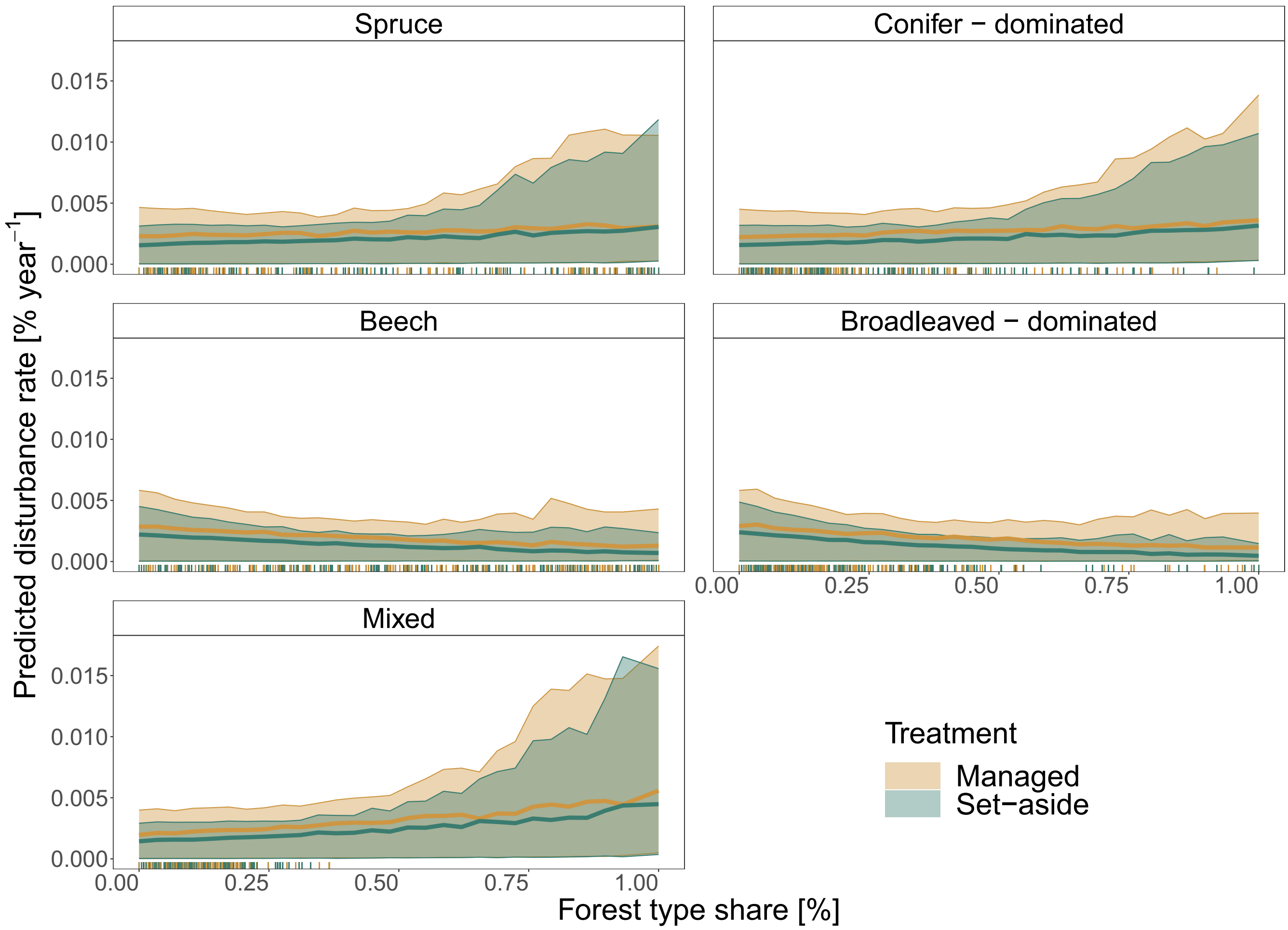

FIGURE 3 Disturbance rate in different forest types and treatments. The line represents the mean disturbance rate; the coloured ribbons represent the 5th–95th quantile of the simulations. The rug represents the data used for fitting the models. Note that three forest types with low representation were excluded from the figure.

forests (Figure 3). While for low shares of spruce, set-aside areas had a lower disturbance rate than managed forests, this difference decreased with increasing spruce share, with similar disturbance rates for spruce shares >90% (Figure 3). For mixed and broadleaved forest types, set-aside areas were consistently less disturbed than managed forests.

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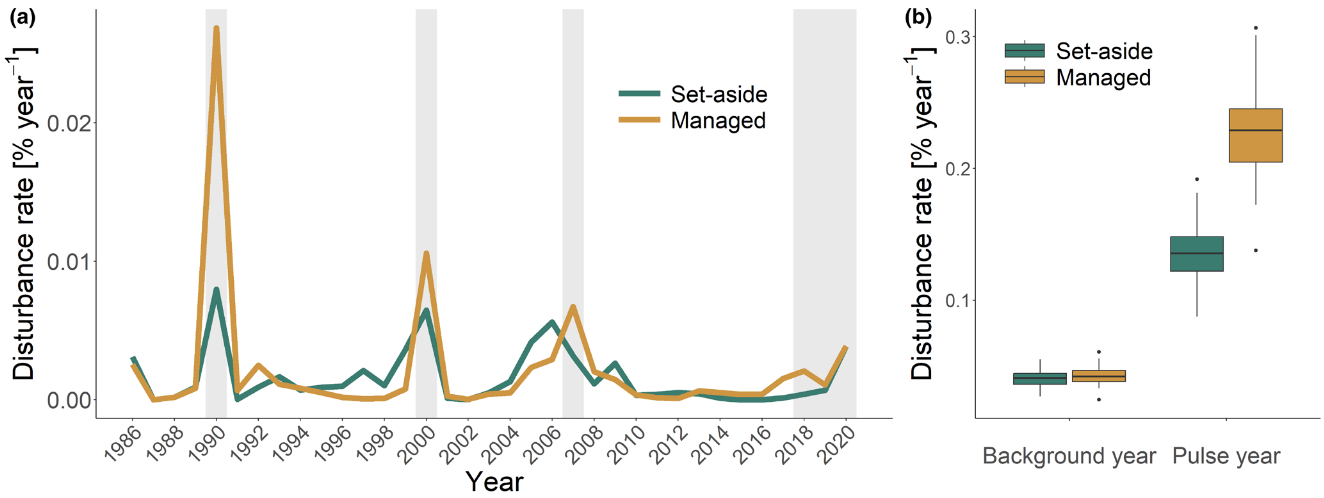

FIGURE 4 (a) Timeseries of mean annual disturbance rates in managed and set-aside sublandscapes. Pulse disturbance years are highlighted in grey. (b) Comparison of disturbance rates in managed and set-aside sublandscapes in pulse and background disturbance years. The boxplot corresponds to the distribution of the bootstrapped models' estimated disturbance rates.

3.2 | Disturbances in pulse and background years

Disturbance dynamics were strongly driven by pulse disturbance years. We found that 56% of the cumulative disturbed area occurred in just six pulse disturbance years (i.e. 1990, 2000, 2007 and 2018–2020) during the 35-year study period. In background years, the annual disturbance rate did not substantially differ between managed (average 0.043% year^{-1}) and set-aside areas (average rate 0.040% year^{-1}). In pulse disturbance years, however, the difference was pronounced: Set-aside areas experienced on average a 40% lower disturbance rate than managed forests, with an average disturbance rate of 0.135% year^{-1} compared with 0.228% year^{-1} (Figure 4). While in set-aside areas the disturbance rate more than tripled in pulse disturbance years compared with background years, we observed a 5.2 times higher disturbance rate in managed forests in pulse years.

4 | DISCUSSION

4.1 | Management impacts on disturbance regime

Here, we analysed disturbance regimes in managed forests and set-aside areas in Germany, showing that forests set aside for conservation have significantly lower disturbance rates and severity than managed forests. This finding supports our first hypothesis (H1) that in set-aside areas, disturbances caused by natural agents manifest at a lower rate. Three processes could contribute to this result: First, set-aside areas are likely more structurally complex, which results in higher resistance to disturbances (Meigs et al., 2017). The presence of multiple canopy layers and an uneven-aged structure was, for instance, found to reduce the likelihood of wind disturbance in previous analyses (Díaz-Yáñez et al., 2017; Mason, 2002; Mohr et al., 2024). Second, active forest management for ecosystem service supply could increase susceptibility to disturbances, with canopy openings created by management interventions increasing susceptibility to disturbances such as wind-throw and bark beetle outbreaks (Jactel et al., 2009; Seidl & Senf, 2024; Stritih et al., 2021). Increased edge density from harvesting, for instance, increases the risk of wind disturbance (Zeng et al., 2009), as do interventions such as thinnings (Albrecht et al., 2012; Stritih et al., 2021). Furthermore, recently exposed edge trees have increased susceptibility to bark beetles (Kautz et al., 2013). Third, post-disturbance management responses can modify disturbance regimes, for example by increasing disturbance severity and disturbance rates through salvage logging operations. Salvage logging is a widespread management response to disturbances in Central Europe, conducted to remove potential breeding material for bark beetles and to recuperate the economic value of disturbed trees (Fettig & Hilszczański, 2015; Wermelinger et al., 1999). However, in salvage logging operations, also surviving trees are often cut, either for operational or economic reasons, which can increase disturbance severity and modify the biological legacies of disturbances (Leverkus et al., 2021; Lindenmayer et al., 2017). We note that we cannot disentangle the contributions of these different mechanisms to the signal found in our data. Hence, the finding of higher disturbance rates and severity in managed areas compared with set-aside areas could also be at least partly the result of post-disturbance management. We suggest that future works could use experimental and simulation approaches to elucidate what drives the differences between managed forests and set-aside areas. Also, while a dedicated analysis using terrestrial data on forest structure was not possible here (as no systematic terrestrial inventory is available for strictly protected areas in Germany), it would be desirable to further investigate the role of differences in structural development trajectories between the investigated strata. Overall, our results of higher disturbance impacts in managed forests compared with set-aside areas are in line with findings from other parts of Europe (Potterf et al., 2023; Stritih et al., 2021) and the globe (Sommerfeld et al., 2018). A novel finding of this contribution is that set-aside areas dampen disturbance activity, particularly in mixed and broadleaved forests (Figure 3), as well as in pulse disturbance years triggered by climatic extremes (Figure 4).

4.2 | Effects in pulse and background years

In pulse disturbance years, we observed an on average 40% lower disturbance rate in set-aside areas compared with managed forests. The observed reduction in disturbance rates in set-aside areas thus approximately doubled in pulse years compared with all observations, supporting our second hypothesis. In pulse years, the ability of management to contain disturbances is often exceeded, reducing the positive effect of active risk management (Hlásny et al., 2021). At the same time, the high visibility of disturbances for the general public in pulse years also increases political and public pressure to conduct salvage and sanitation logging (Müller, 2011), which might further increase disturbance severity in managed forests. Furthermore, the potential dampening effects of a more complex stand structure in set-aside forests might become more prominent in pulse years, as spatial variability can effectively dampen the spread of disturbances (Seidl et al., 2016). Overall, our results indicate that setting aside areas for conservation dampens peak disturbance pulses and reduces the contribution of pulse years to total disturbance activity.

4.3 | Limitations

Important methodological aspects need to be considered when interpreting our results. First, the agent attribution used to identify disturbances triggered by natural causes (Seidl & Senf, 2024) is associated with uncertainties (Senf & Seidl, 2021b). But as the disturbance attribution achieved an overall classification accuracy of 93% in a European-scale validation (Seidl & Senf, 2024), we expect the impact of these uncertainties on our analyses to be limited. To further test for different disturbance detection probabilities between managed and set-aside forests, we conducted an additional validation (Figure S9), indicating no differences between the analysed strata. A further limitation of our approach is that the 30 m × 30 m resolution of the Landsat-based disturbance map results in the omission of small disturbed patches. This likely affects estimates of disturbance rate, patch size and frequency, and could bias results as we generally expect smaller disturbance patches in protected areas (Krüger et al., 2024). Furthermore, we note that the disturbance data analysed here do not include low-severity disturbances, and hence only capture a subset of the disturbance regime. Importantly, the reserves and natural parks studied here are not primary forests (Sabatini et al., 2018). Frequently, they were managed in the past and are characterized by considerable land-use legacies (Frelich et al., 2018). To reduce this effect, we selected reserves where forest management had ceased already by 1986, balancing sample size and the potential influence of past management.

5 | CONCLUSIONS

Three important implications arise from our work: first, we found that strict forest reserves do not experience higher rates of disturbance than managed forests; hence, setting aside forests for biodiversity conservation does not amplify disturbance activity. The latter is an argument frequently voiced among managers in Central Europe, yet it is not supported by our data. In contrast, our finding of lower disturbance rates and severities in set-aside areas suggests that including reserves in landscape-scale forest planning in Central Europe could even dampen forest disturbance pulses. It is noteworthy that significant differences could already be found 35 years after reserves were set aside, underlining the effect of naturally developing forests already in the first decades after the cessation of management (Albrich et al., 2021; Potterf et al., 2023). Second, our analyses underline the high importance of forest reserve networks for Central Europe. These reserves are usually much smaller than higher profile protected areas such as national parks but are also easier to instate and maintain. They can serve as nuclei of natural development in a landscape strongly modified by humans and cover a much broader range of forest types than large protected areas do. This is important as forest management in Central Europe generally aims to move 'closer-to-nature' (Larsen et al., 2022), yet references for natural conditions are often absent. Lastly, our results indicate that traditional ways of managing disturbances have not reduced disturbance risk over the counterfactual of a development without active risk management in set-aside areas. This suggests that we need to explore new ways of addressing disturbances in forest management. One approach could be to more strongly embrace disturbances in management by actively utilizing their patterns and legacies in silviculture (Aszalós et al., 2022) and by considering a compensation between natural and human canopy openings (Seidl & Senf, 2024). While forest management in Central Europe has focused strongly on preventing disturbances in the past (Fettig & Hilszczański, 2015; Stadelmann et al., 2013), an important future focus of management could be to foster disturbance resilience (Messier et al., 2019), that is strengthening the response to and recovery from disturbances while utilizing post-disturbance reorganization to shape the future of our forests.

AUTHOR CONTRIBUTIONS

Kirsten Krüger: conceptualization, methodology, formal analysis, writing—original draft and visualization. **Cornelius Senf:** conceptualization, methodology and writing—review and editing. **Jonas Hagge:** conceptualization, Writing—review and editing. **Rupert Seidl:** conceptualization, methodology, writing—review and editing and supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data and code of the analysis are available at Zenodo: https://doi.org/10.5281/zenodo.14990256 (Krüger, 2025).

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REFERENCES

Albrecht, A., Hanewinkel, M., Bauhus, J., & Kohnle, U. (2012). How does silviculture affect storm damage in forests of south-western Germany? Results from empirical modeling based on long-term observations. *European Journal of Forest Research*, *131*(1), 229–247. https://doi.org/10.1007/s10342-010-0432-x

Albrich, K., Thom, D., Rammer, W., & Seidl, R. (2021). The long way back: Development of Central European mountain forests towards old-growth conditions after cessation of management. *Journal of Vegetation Science*, *32*(4), e13052. https://doi.org/10.1111/jvs.13052

Aszalós, R., Thom, D., Aakala, T., Angelstam, P., Brūmelis, G., Gálhidy, L., Gratzer, G., Hlásny, T., Katzensteiner, K., Kovács, B., Knoke, T., Larrieu, L., Motta, R., Müller, J., Ódor, P., Roženbergar, D., Paillet, Y., Pitar, D., Standovár, T., … Keeton, W. S. (2022). Natural disturbance regimes as a guide for sustainable forest management in Europe. *Ecological Applications*, *32*(5), e2596. https://doi.org/10.1002/eap.2596

Blickensdörfer, L., Oehmichen, K., Pflugmacher, D., Kleinschmit, B., & Hostert, P. (2024). National tree species mapping using Sentinel-1/2 time series and German National Forest Inventory data. *Remote Sensing of Environment*, *304*, 114069. https://doi.org/10.1016/j.rse.2024.114069

Brooks, M. E., Kristensen, K., Benthem, K. J., van Magnusson, A., Berg, C. W., Nielsen, A., Skaug, H. J., Mächler, M., & Bolker, B. M. (2017). glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R Journal*, *9*(2), 378–400.

Díaz-Yáñez, O., Mola-Yudego, B., González-Olabarria, J. R., & Pukkala, T. (2017). How does forest composition and structure affect the stability against wind and snow? *Forest Ecology and Management*, *401*, 215–222. https://doi.org/10.1016/j.foreco.2017.06.054

Evans, J. S., Murphy, M. A., & Ram, K. (2023). *Package 'spatialEco'—Spatial analysis and modelling utilities* (version 2.0-2) [R]. https://archive.linux.duke.edu/cran/web/packages/spatialEco/spatialEco.pdf

Fettig, C. J., & Hilszczański, J. (2015). Chapter 14—Management strategies for bark beetles in conifer forests. In F. E. Vega & R. W. Hofstetter (Eds.), *Bark beetles* (pp. 555–584). Academic Press. https://doi.org/10.1016/B978-0-12-417156-5.00014-9

Frelich, L. E., Jõgiste, K., Stanturf, J. A., Parro, K., & Baders, E. (2018). Natural disturbances and forest management: Interacting patterns on the landscape. In A. H. Perera, U. Peterson, G. M. Pastur, & L. R. Iverson (Eds.), *Ecosystem services from forest landscapes: Broadscale considerations* (pp. 221–248). Springer International Publishing. https://doi.org/10.1007/978-3-319-74515-2_8

Gauer, J., Kroiher, F., & Johann Heinrich von Thünen-Institut. (2012). *Waldökologische Naturräume Deutschlands: Forstliche Wuchsgebiete und Wuchsbezirke; digitale topographische Grundlagen*. (Digitale topographische Grundlagen, Neubearb., Stand 2011). Johann Heinrich von Thünen-Inst.

Giuggiola, A., Bugmann, H., Zingg, A., Dobbertin, M., & Rigling, A. (2013). Reduction of stand density increases drought resistance in xeric scots pine forests. *Forest Ecology and Management*, *310*, 827–835. https://doi.org/10.1016/j.foreco.2013.09.030

Hanewinkel, M., Hummel, S., & Albrecht, A. (2011). Assessing natural hazards in forestry for risk management: A review. *European Journal of Forest Research*, *130*(3), 329–351. https://doi.org/10.1007/s10342-010-0392-1

Hijmans, R. J., Bivand, R., Pebesma, E., & Sumner, M. D. (2023). *terra: Spatial data analysis* (version 1.7-39) [software]. https://cran.r-project.org/web/packages/terra/index.html

Hirschmugl, M., Gallaun, H., Dees, M., Datta, P., Deutscher, J., Koutsias, N., & Schardt, M. (2017). Methods for mapping forest disturbance and degradation from optical earth observation data: A review. *Current Forestry Reports*, *3*(1), 32–45. https://doi.org/10.1007/s40725-017-0047-2

Hlásny, T., Zimová, S., Merganičová, K., Štěpánek, P., Modlinger, R., & Turčáni, M. (2021). Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications. *Forest Ecology and Management*, *490*, 119075. https://doi.org/10.1016/j.foreco.2021.119075

Jactel, H., Nicoll, B. C., Branco, M., Gonzalez-Olabarria, J. R., Grodzki, W., Långström, B., Moreira, F., Netherer, S., Orazio, C., Piou, D., Santos, H., Schelhaas, M. J., Tojic, K., & Vodde, F. (2009). The influences of forest stand management on biotic and abiotic risks of damage. *Annals of Forest Science*, *66*(7), 701. https://doi.org/10.1051/forest/2009054

Jakoby, O., Lischke, H., & Wermelinger, B. (2019). Climate change alters elevational phenology patterns of the European spruce bark beetle (*Ips typographus*). *Global Change Biology*, *25*(12), 4048–4063. https://doi.org/10.1111/gcb.14766

Johnson, C. N., Balmford, A., Brook, B. W., Buettel, J. C., Galetti, M., Guangchun, L., & Wilmshurst, J. M. (2017). Biodiversity losses and conservation responses in the Anthropocene. *Science*, *356*(6335), 270–275. https://doi.org/10.1126/science.aam9317

Juutinen, A., Haeler, E., Jandl, R., Kuhlmey, K., Kurttila, M., Mäkipää, R., Pohjanmies, T., Rosenkranz, L., Skudnik, M., Triplat, M., Tolvanen, A., Vilhar, U., Westin, K., & Schueler, S. (2022). Common preferences of European small-scale forest owners towards contract-based management. *Forest Policy and Economics*, *144*, 102839. https://doi.org/10.1016/j.forpol.2022.102839

Kautz, M., Schopf, R., & Ohser, J. (2013). The "sun-effect": Microclimatic alterations predispose forest edges to bark beetle infestations. *European Journal of Forest Research*, *132*(3), 453–465. https://doi.org/10.1007/s10342-013-0685-2

Krüger, K. (2025). Setting aside areas for conservation does not increase disturbances in temperate forests – Data and analysis scripts [Data set]. *Zenodo*. https://doi.org/10.5281/zenodo.14990256

Krüger, K., Senf, C., Jucker, T., Pflugmacher, D., & Seidl, R. (2024). Gap expansion is the dominant driver of canopy openings in a temperate mountain forest landscape. *Journal of Ecology*, *112*(7), 1501–1515. https://doi.org/10.1111/1365-2745.14320

Kulakowski, D., Buma, B., Guz, J., & Hayes, K. (2020). The ecology of forest disturbances. In M. I. Goldstein & D. A. DellaSala (Eds.), *Encyclopedia of the world's biomes* (pp. 35–46). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.11878-0

Larsen, J. B., Angelstam, P., Bauhus, J., Carvalho, J. F., Diaci, J., Dobrowolska, D., Gazda, A., Gustafsson, L., Krumm, F., Knoke, T., Konczal, A., Kuuluvainen, T., Mason, B., Motta, R., Pötzelsberger, E., Rigling, A., & Schuck, A. (2022). *Closer-to-nature forest management (from science to policy)*. European Forest Institute. https://doi.org/10.36333/fs12

Leverkus, A. B., Buma, B., Wagenbrenner, J., Burton, P. J., Lingua, E., Marzano, R., & Thorn, S. (2021). Tamm review: Does salvage logging mitigate subsequent forest disturbances? *Forest Ecology and Management*, *481*, 118721. https://doi.org/10.1016/j.foreco.2020.118721

Lindenmayer, D., Thorn, S., & Banks, S. (2017). Please do not disturb ecosystems further. *Nature Ecology & Evolution*, *1*(2), 31. https://doi.org/10.1038/s41559-016-0031

Mason, W. L. (2002). Are irregular stands more windfirm? *Forestry*, *75*(4), 347–355. https://doi.org/10.1093/forestry/75.4.347

Mathes, T., Seidel, D., & Annighöfer, P. (2023). Response to extreme events: Do morphological differences affect the ability of beech (*Fagus sylvatica* L.) to resist drought stress? *Forestry*, *96*(3), 355–371. https://doi.org/10.1093/forestry/cpac056

McDowell, N. G., Allen, C. D., Anderson-Teixeira, K., Aukema, B. H., Bond-Lamberty, B., Chini, L., Clark, J. S., Dietze, M., Grossiord, C., Hanbury-Brown, A., Hurtt, G. C., Jackson, R. B., Johnson, D. J., Kueppers, L., Lichstein, J. W., Ogle, K., Poulter, B., Pugh, T. A. M., Seidl, R., … Xu, C. (2020). Pervasive shifts in forest dynamics in a changing world. *Science*, *368*(6494), eaaz9463. https://doi.org/10.1126/science.aaz9463

Meigs, G. W., Morrissey, R. C., Bače, R., Chaskovskyy, O., Čada, V., Després, T., Donato, D. C., Janda, P., Lábusová, J., Seedre, M., Mikoláš, M., Nagel, T. A., Schurman, J. S., Synek, M., Teodosiu, M., Trotsiuk, V., Vítková, L., & Svoboda, M. (2017). More ways than one: Mixed-severity disturbance regimes foster structural complexity via multiple developmental pathways. *Forest Ecology and Management*, *406*, 410–426. https://doi.org/10.1016/j.foreco.2017.07.051

Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., Mina, M., Aquilué, N., Fortin, M.-J., & Puettmann, K. (2019). The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, *6*(1), 21. https://doi.org/10.1186/s40663-019-0166-2

Mohr, J., Thom, D., Hasenauer, H., & Seidl, R. (2024). Are uneven-aged forests in Central Europe less affected by natural disturbances than even-aged forests? *Forest Ecology and Management*, *559*, 121816. https://doi.org/10.1016/j.foreco.2024.121816

Müller, M. (2011). How natural disturbance triggers political conflict: Bark beetles and the meaning of landscape in the Bavarian Forest. *Global Environmental Change*, *21*(3), 935–946. https://doi.org/10.1016/j.gloenvcha.2011.05.004

Oliver, T. H. (2018). Biodiversity generation and loss. In *Oxford research encyclopedia of environmental science*. Oxford University Press. https://oxfordre.com/environmentalscience/view/10.1093/acrefore/9780199389414.001.0001/acrefore-9780199389414-e-96

Patacca, M., Lindner, M., Lucas-Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., Hauf, Y., Jasinevičius, G., Labonne, S., Linkevičius, E., Mahnken, M., Milanovic, S., Nabuurs, G.-J., Nagel, T. A., Nikinmaa, L., Panyatov, M., Bercak, R., Seidl, R., Ostrogović Sever, M. Z., … Schelhaas, M.-J. (2022). Significant increase in natural disturbance impacts on European forests since 1950. *Global Change Biology*, *29*(5), 1359–1376. https://doi.org/10.1111/gcb.16531

Potterf, M., Svitok, M., Mezei, P., Jarčuška, B., Jakuš, R., Blaženec, M., & Hlásny, T. (2023). Contrasting Norway spruce disturbance dynamics in managed forests and strict forest reserves in Slovakia. *Forestry*, *96*(3), 387–398. https://doi.org/10.1093/forestry/cpac045

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Riedel, T., Bender, S., Hennig, P., Kroiher, F., Schnell, S., Schwitzgebel, F., Stauber, T., Stahlmann, J. K., & Kühling, M. (2024). *Der Wald in Deutschland—Ausgewählte Ergebnisse der vierten Bundeswaldinventur*. Bundesministerium für Ernährung und Landwirtschaft (BMEL).

Sabatini, F. M., Burrascano, S., Keeton, W. S., Levers, C., Lindner, M., Pötzschner, F., Verkerk, P. J., Bauhus, J., Buchwald, E., Chaskovsky, O., Debaive, N., Horváth, F., Garbarino, M., Grigoriadis, N., Lombardi, F., Duarte, I. M., Meyer, P., Midteng, R., Mikac, S., … Kuemmerle, T. (2018). Where are Europe's last primary forests? *Diversity and Distributions*, *24*(10), 1426–1439. https://doi.org/10.1111/ddi.12778

Seidel, D., & Ammer, C. (2023). Towards a causal understanding of the relationship between structural complexity, productivity, and adaptability of forests based on principles of thermodynamics. *Forest Ecology and Management*, *544*, 121238. https://doi.org/10.1016/j.foreco.2023.121238

Seidl, R. (2014). The shape of ecosystem management to come: Anticipating risks and fostering resilience. *BioScience*, *64*(12), 1159–1169. https://doi.org/10.1093/biosci/biu172

Seidl, R., Donato, D. C., Raffa, K. F., & Turner, M. G. (2016). Spatial variability in tree regeneration after wildfire delays and dampens future bark beetle outbreaks. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(46), 13075–13080. https://doi.org/10.1073/pnas.1615263113

Seidl, R., Fernandes, P. M., Fonseca, T. F., Gillet, F., Jönsson, A. M., Merganičová, K., Netherer, S., Arpaci, A., Bontemps, J.-D., Bugmann, H., González-Olabarria, J. R., Lasch, P., Meredieu, C., Moreira, F., Schelhaas, M.-J., & Mohren, F. (2011). Modelling natural disturbances in forest ecosystems: A review. *Ecological Modelling*, *222*(4), 903–924. https://doi.org/10.1016/j.ecolmodel.2010.09.040

Seidl, R., & Senf, C. (2024). Changes in planned and unplanned canopy openings are linked in Europe's forests. *Nature Communications*, *15*(1), 4741. https://doi.org/10.1038/s41467-024-49116-0

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M. J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T. A., & Reyer, C. P. O. (2017). Forest disturbances under climate change. *Nature Climate Change*, *7*, 395–402. https://doi.org/10.1038/nclimate3303

Senf, C. (2022). Seeing the system from above: The use and potential of remote sensing for studying ecosystem dynamics. *Ecosystems*, *25*(8), 1719–1737. https://doi.org/10.1007/s10021-022-00777-2

Senf, C., Pflugmacher, D., Zhiqiang, Y., Sebald, J., Knorn, J., Neumann, M., Hostert, P., & Seidl, R. (2018). Canopy mortality has doubled in Europe's temperate forests over the last three decades. *Nature Communications*, *9*(1), 4978. https://doi.org/10.1038/s41467-018-07539-6

Senf, C., & Seidl, R. (2021a). Mapping the forest disturbance regimes of Europe. *Nature Sustainability*, *4*(1), 63–70. https://doi.org/10.1038/s41893-020-00609-y

Senf, C., & Seidl, R. (2021b). Storm and fire disturbances in Europe: Distribution and trends. *Global Change Biology*, *27*(15), 3605–3619. https://doi.org/10.1111/gcb.15679

Sommerfeld, A., Senf, C., Buma, B., D'Amato, A. W., Després, T., Díaz-Hormazábal, I., Fraver, S., Frelich, L. E., Gutiérrez, Á. G., Hart, S. J., Harvey, B. J., He, H. S., Hlásny, T., Holz, A., Kitzberger, T., Kulakowski, D., Lindenmayer, D., Mori, A. S., Müller, J., … Seidl, R. (2018). Patterns and drivers of recent disturbances across the temperate forest biome. *Nature Communications*, *9*(1), 4355. https://doi.org/10.1038/s41467-018-06788-9

Spiecker, H. (2003). Silvicultural management in maintaining biodiversity and resistance of forests in Europe—Temperate zone. *Journal of Environmental Management*, *67*(1), 55–65. https://doi.org/10.1016/S0301-4797(02)00188-3

Stadelmann, G., Bugmann, H., Meier, F., Wermelinger, B., & Bigler, C. (2013). Effects of salvage logging and sanitation felling on bark beetle (*Ips typographus* L.) infestations. *Forest Ecology and Management*, *305*, 273–281. https://doi.org/10.1016/j.foreco.2013.06.003

Steinacker, C., Engel, F., & Meyer, P. (2023). Natürliche Waldentwicklung in Deutschland: Auf dem Weg zum 5%-Ziel der Nationalen Strategie zur biologischen Vielfalt. *Naturschutz und Landschaftsplanung*, *98*(12), 545–552. https://doi.org/10.19217/NuL2023-12-01

Stritih, A., Senf, C., Seidl, R., Grêt-Regamey, A., & Bebi, P. (2021). The impact of land-use legacies and recent management on natural disturbance susceptibility in mountain forests. *Forest Ecology and Management*, *484*, 118950. https://doi.org/10.1016/j.foreco.2021.118950

Thorn, S., Bässler, C., Brandl, R., Burton, P. J., Cahall, R., Campbell, J. L., Castro, J., Choi, C., Cobb, T., Donato, D. C., Durska, E., Fontaine, J. B., Gauthier, S., Hebert, C., Hothorn, T., Hutto, R. L., Lee, E., Leverkus, A. B., Lindenmayer, D. B., … Müller, J. (2018). Impacts of salvage logging on biodiversity: A meta-analysis. *Journal of Applied Ecology*, *55*(1), 279–289. https://doi.org/10.1111/1365-2664.12945

Thünen-Institut. (2022). *Wuchsgebiete 2020. Thünen Atlas*. https://atlas.thuenen.de/layers/wgwb:geonode:wgwb_wg_2020

Turner, M. G., Gardner, R. H., & O'Neill, R. V. (2001). *Landscape ecology in theory and practice: Pattern and process*. Springer.

Turner, M. G., & Seidl, R. (2023). Novel disturbance regimes and ecological responses. *Annual Review of Ecology, Evolution, and Systematics*, *54*(1), 63–83. https://doi.org/10.1146/annurev-ecolsys-110421-101120

UNEP. (2022). *Kunming-Montreal global biodiversity framework*. Convention on Biological Diversity.

Urban, D. L., O'Neill, R. V., & Shugart, H. H., Jr. (1987). Landscape ecology. *BioScience*, *37*(2), 119–127. https://doi.org/10.2307/1310366

Valeria, M., Coralie, B., Petr, D., Susanne, K., Jan, O., Christian, S., & Yoshan, M. (2016). How differential management strategies affect *Ips typographus* L. dispersal. *Forest Ecology and Management*, *360*, 195–204. https://doi.org/10.1016/j.foreco.2015.10.037

Wermelinger, B., Obrist, M. K., Duelli, P., & Forster, B. (1999). Development of the bark beetle (Scolytidae) fauna in windthrow areas in Switzerland. *Mitteilungen der Schweizerischen Entomologischen Gesellschaft*, *72*(3/4), 209–220.

Wohlgemuth, T., Hanewinkel, M., & Seidl, R. (2022). Wind disturbances. In T. Wohlgemuth, A. Jentsch, & R. Seidl (Eds.), *Disturbance ecology* (pp. 173–194). Springer International Publishing. https://doi.org/10.1007/978-3-030-98756-5_8

Zeng, H., Peltola, H., Väisänen, H., & Kellomäki, S. (2009). The effects of fragmentation on the susceptibility of a boreal forest ecosystem to wind damage. *Forest Ecology and Management*, *257*(3), 1165–1173. https://doi.org/10.1016/j.foreco.2008.12.003

Zöller, L., Beierkuhnlein, C., Faust, D., & Samimi, C. (2017). *Die Physische Geographie Deutschlands*. Wissenschaftliche Buchgesellschaft (WBG).

SUPPORTING INFORMATION

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

Text S1. Additional methods.

Text S2. Additional results.

Text S3. Sensitivity analysis high severity threshold.

Text S4. Validation analysis of disturbance detection in managed and set-aside forests.

Table S1. Rule for down sampling large set-aside forests.

Table S2. List of disturbance metrics. Metrics were calculated on all forested 30 m × 30 m resolution pixels within a sublandscape.

Table S3. Total area disturbed (ha) in pulse and background disturbance years.

Table S4. Mean model estimates with the 95th confidence interval for all disturbance metrics for the 1:1 and 1:many matching design.

Table S5. Results for sensitivity analysis of threshold choice for high severity disturbances.

Figure S1. Aggregated forest type map based on Blickensdörfer et al. (2024).

Figure S2. Distribution of environmental variables for 1:1 matched managed and set-aside sublandscapes.

Figure S3. Distribution of distances between matched landscapes. Red triangle marks the mean distance between matched landscapes.

Figure S4. Forest type composition of 1:1 match for managed and set-aside forest landscapes.

Figure S5. Share of realized forest types on areas covered by potential natural vegetation (PNV).

Figure S6. Variability in random intercepts for disturbance rates across ecoregions.

Figure S7. Effect of non-management on the disturbance rate per ecoregion.

Figure S8. Deviation of total area disturbed in each observation year from the across-year-average (0).

Figure S9. Confusion matrix of validation points for disturbance detection in managed and set-aside forests between 2000 and 2020.

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