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Are natural disturbances represented in strictly protected areas in Germany?

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A B S T R A C T

Natural disturbances are largely suppressed in Central European landscapes due to economic and human safety concerns. European goals to increase the extent of secondary wilderness areas have the potential to support the restoration of threatened habitats associated with natural disturbances. Germany is among the Central European countries with the most advanced wilderness goals. This study aimed to investigate whether habitat types shaped by natural disturbances are mostly red-listed as threatened and require special consideration within systematic conservation planning (SCP). First, we reviewed literature and the German Red List of Threatened Habitat Types to identify the conservation status of habitat types associated with three natural abiotic disturbance types in Germany: floods, forest fires and landslides. Second, we mapped the potential area coverage of these disturbance types and identified gaps in the current network of strictly protected areas (PA) to inform SCP. Fifty-two per cent of the habitat types associated with the three disturbance types floods, forest fires and landslides were listed as "critically endangered" ($n = 1$) or "endangered to critically endangered" ($n = 9$). The potential area for river dynamics accounted for 4.3% of German terrestrial territory, areas potentially subject to forest fires accounted for 0.9% and areas with a very high susceptibility to landslides for 1.1%. Areas potentially subject to forest fires (0.15% strict PA coverage) and river dynamics (0.81%) were underrepresented in German National Parks and the core zones of Biosphere Reserve, whereas strict PA coverage of areas with a very high susceptibility to landslides was higher (6.8%). European and German wilderness goals can support the restoration of threatened habitat types associated with natural disturbances if spatial information on those areas is integrated into SCP concepts. Yet, sophisticated management regimes will be required to resolve conflicts between wilderness areas subject to natural disturbances and the surrounding cultural landscape and infrastructure.

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1. Introduction

Conservation biology aims to “provide principles and tools for preserving biological diversity” (Soulé, 1985, p. 1). Systematic conservation planning (hereafter SCP) is one tool to reach conservation goals, for example by systematically locating and designing protected areas (Margules and Pressey, 2000). Ideally, protected areas represent biodiversity patterns at different spatial scales and help to ensure their persistence (Margules and Pressey, 2000). Globally, the remaining, relatively pristine wilderness areas in Asia, America, Africa and Australia are considered priorities for biodiversity conservation through the implementation of protected areas (Mittermeier et al., 2003; Anderson and Mammides, 2019). Here, biologically intact ecosystems could persist as very low levels of human activity sustained biodiversity and the related ecological processes (Bryant et al., 1997; Watson et al., 2016). In contrast, the terrestrial ecosystems in Central Europe were widely transformed into cultural landscapes, so that today few wilderness areas remain (Rosenthal et al., 2015; Brackhane et al., 2019a). Natural disturbances, defined by type, frequency, return interval, spatial extent, intensity (energy flow per areas per time) and severity (magnitude of impact), are an important factor initiating natural dynamics and create site-specific habitats (Navarro et al., 2015; Picket and White, 1985). For example, natural disturbances such as fires, landslides, floods and megaherbivory, were crucial for creating open and early-successional habitats in the forest-dominated Central European landscapes under the absence of human activities (Svenning, 2002). Today, natural disturbances are largely suppressed in this region due to economic or human safety concerns (Morgan and Rickson, 2003; Vergani et al., 2017; San-Miguel-Ayanz et al., 2018), despite being an important site factor for a variety of habitats and associated biodiversity (Trémolières et al., 1998; Thom and Seidl, 2016; Gutowski et al., 2020). This has led to a steep decline in entire ecosystems that are shaped by natural disturbances, such as flood-dependent riparian wetlands (Brown et al., 2018), or resulted in the absence of typical habitat and vegetation mosaics within certain forest ecosystems (e.g. early successional phases in mountain forest following landslides).

In recent years, reintroducing natural disturbances to Central European ecosystems gained attention among scientists and land managers. For example, “rewilding” is increasingly discussed as a conservation tool to restore natural dynamics and associated, but widely lost, habitats (Pereira and Navarro, 2015; Jepson, 2016). (Perino et al., 2019) distinguish between active rewilding, where the reintroduction of natural processes is triggered actively by human interventions, e.g. the (re-)introduction of native or non-native wildlife to an ecosystem (Corlett, 2016). In contrast, passive rewilding focuses on the strict protection of areas where natural processes can develop after eliminating major human interferences. Passive rewilding approaches have already been implemented in Central Europe, e.g. in the form of strictly protected core zones in National Parks (Synge, 2004). The European Union aims at increasing the extent of strictly protected areas (hereafter strict PAs) to halt the loss of biodiversity in line with the Convention on Biological Diversity (European Commission, 2013, 2020). Similarly, the German “wilderness” strategy aims to implement strict PAs on 2% of the country’s terrestrial territory (Küchler-Krischun and Walter, 2007; Brackhane et al., 2019a). The ((European Commission, 2020), p. 5) states that “strict protection (…) leaves natural processes essentially undisturbed to respect the areas’ ecological requirements”. In the context of Germany, wilderness areas are defined as “sufficiently large, (predominantly) non-fragmented areas free of intrusive or extractive human activity. They serve to permanently provide for the ecological functioning of natural processes without human interference” (Finck et al., 2013; Schumacher et al., 2018). These secondary wilderness areas will have to evolve largely from formerly used cultural landscapes.

The wilderness goals of the European Union and Germany raise the question, if threatened habitats shaped by natural disturbances can be restored if relevant areas are prioritized within SCP schemes. Economic and human safety concerns may be less vital in strict PAs where human activities are largely excluded. In this context, mapping the potential role of natural disturbances within Central European ecosystems is a crucial (Müller et al., 2019), but difficult task. Natural disturbances and associated dynamics have been widely excluded from Central European ecosystems for centuries, so that adequate reference areas are often missing. Relevant natural disturbance types include those associated with biotic disturbances such as megaherbivores (e.g. European bison, moose; Svenning et al., 2016) and abiotic disturbances such as fires, avalanches, floods, storms and landslides (Wohlgemuth et al., 2019). Since major knowledge gaps exist regarding the role of natural disturbances in Central Europe, surrogates and indicator datasets may be used to accumulate information that can support SCP. Gap analysis, as described by (Scott et al., 1993), uses existing datasets and Geographic Information Systems to identify gaps in vegetation types or species assemblages that are not represented in the current protected area network. These gaps may be filled through the establishment of new protected areas. In the context of natural disturbances in Central Europe, there is still a need to identify disturbance-dependent habitats, their conservation status, and their potential spatial distribution. If disturbance-dependent habitats and species are indeed threatened, gap analysis can assess if they are adequately covered by protected areas or other conservation measures.

In this study we mapped the potential occurrence of selected natural disturbance types and conducted a protected area gap analysis for areas potentially subject to natural disturbances in Germany. Germany was selected as a case study because it has the most advanced wilderness goals among Central European states despite its high population density (Brackhane et al., 2019a). We drew upon Picket and White (1985) in defining disturbance as any relatively discrete event in time that disrupts ecosystem, community or population structure and changes resources, substrate availability, or the physical environment. Whereas storms and insect outbreaks prevail as major natural disturbances in the culturally dominated ecosystems in Central Europe (esp. forests) (Schelhaas et al., 2003), we assumed that, without human interference, a variety of abiotic disturbance regimes would shape the German landscape at different spatial and temporal scales (Picket and White, 1985). Here, we mapped the potential spatial distribution of floods, forest fires, and landslides, which are nowadays largely suppressed and hence possibly underrepresented in Central European ecosystems. In particular, we:

1) Reviewed literature and the Red List of Threatened Habitat Types of Germany to identify all threatened habitat types that depend on one or more of the selected abiotic natural disturbances: floods, forest fires, and landslides.
2) Mapped the spatial potential for floods, forest fires, and landslides across Germany and more specifically across the seven German ecoregions.
3) Conducted a protected area gap analysis that assessed the current coverage of strict PAs (i.e., IUCN protected area categories I and II) for the areas potentially subject to the three disturbance types.

If habitat types shaped by natural disturbances are indeed mostly red-listed as threatened and not adequately represented in the current network of strict PAs in Germany, then their integration into concepts of SCP would be required.

2. Methods

2.1. Area of study

The study concentrates on the Federal Republic of Germany, located in the heart of Central Europe (Fig. 1). Germany is one of the largest (35,757,817 ha) and most populated European countries, with over 83 million inhabitants and a population density of 234 people per km^2 (Statistisches, 2019). Temperate forests of *Fagus sylvatica* are the dominant potential natural vegetation (hereafter PNV; Bohn et al., 2000) in Germany extending over Atlantic and continental climate zones (Frey and Lösch, 2010). Today, forests cover approximately 32% (11.4 mill ha) of the German territory (Polley et al., 2016). In past centuries, vast extents of natural forests were transformed into monocultures of *Picea abies* and *Pinus sylvestris*. The mean annual temperature in Germany was 8.9 °C and the annual mean precipitation was 819 mm for the period 1981–2010 (Deutscher Wetterdienst, 2020). In Germany, four major ecoregions can be distinguished according to geomorphological, geological, hydrological and biogeographical criteria; these include the relatively flat North German Lowlands, the mountainous Central German Uplands (≤1500 m above sea level, a.s.l.), the Alpine Foothills and the Alps (1500–2962 m a.s.l.) (Fig. 1; Otremba and Meynen, 1948). To enable a more detailed spatial analysis, we divided the ecoregion “North German Lowlands” into a western (Northwest German Lowlands, NW Lowlands) and eastern part (Northeast German Lowlands, NE Lowlands), and the Central German Uplands in Western (W), Southwestern (SW) and Eastern (E) components following Brackhane et al. (2019a). There are 79 rivers with a watershed ≥1000 km^2 in Germany (Harms et al., 2018).

2.2. Red List status of habitat types

We used the third edition of the ‘German Red List of Threatened Habitat Types’ (Finck et al., 2017; Heinze et al., 2020), expert knowledge and literature review (Google scholar; Keywords: habitat type x disturbance x disturbance type) to identify the number and Red List status of terrestrial habitats shaped by the natural disturbance types floods, forest fires and landslides. We only included habitat types with an obligate relation to one of these natural disturbance types, but did not consider those with a facultative association, *inter alia* habitat types that are resilient to – but not necessarily dependent on – natural disturbances. Obligate habitat types include floodplain habitats that would be replaced by more competitive species under the absence of natural river dynamics, including flood regimes (Bayley, 1995). Scots pine forest communities, especially those on dry and sandy sites, may constitute an example for a habitat type shaped by fires under the absence of any human interventions (e.g. Dicrano-Pinion; Matthews, 1993; Niklasson et al., 2010; Dittrich et al., 2016). Landslides often result in bare soils and provide habitat for many early-successional plant species, but also for wildlife, such as various wild bee species that depend on such biotopes for nesting (Westrich, 1996).

2.3. Disturbances

2.3.1. Floods

We included all terrestrial land area in Germany that would be shaped by large rivers under natural conditions, including habitats created by floods (e.g. hardwood alluvial plain). We used the geodataset “Floodplain segments” provided by the-Federal Agency for Nature Conservation, 2009, created using Geobasisdaten © GeoBasis-DE / BKG (2009) to quantify the spatial potential for natural dynamics in major river systems in Germany (Koenzen and Günther-Diringer, 2009; Supplementary Material S1, Fig. 2A). The dataset included 79 German rivers, with a watershed of at least 1,000 km^2 and a total length of 10,276 km (Brunotte et al., 2009). The dataset distinguished between three segments of the morphological floodplain: i) the river, ii) the contiguous floodplain which is still subject to river dynamics (floods); and iii) the historic floodplain, which is disconnected from the river through dams and other anthropogenic infrastructure (Harms et al., 2018). The three segments combined represent the potential area of river dynamics under natural conditions in 79 major rivers in Germany (Harms et al., 2018); and consequently the potential area for floods. We evaluated the number and spatial extent of

Fig. 1. The area of study, including the location of seven ecoregions, major waterbodies, elevation, terrestrial cover of protected area types relevant to this study and four major cities >1 Mill. inhabitants. Core zones of Biosphere Reserves are too small to be adequately depicted in the map. We depicted the full extent of Biosphere Reserves comprising the core zones (data on protected areas was provided by the Federal Agency for Nature Conservation, 2019).

areas ≥500 ha in the contiguous floodplain because these areas may constitute candidate sites for wilderness areas in line with minimum criteria of the German National Strategy on Biological Diversity (Brackhane et al., 2019b). Wilderness areas in the other two river segments would demand a limitation of shipping or the relocation of dams. This might be locally feasible, but rarely for all major rivers of Germany.

2.3.2. Forest fires

We evaluated the potential for naturally occurring forest fires in Germany by combining three datasets: 1) the map of the potential natural vegetation (PNV; Bohn et al., 2000; S1, Fig. 2D) and 2) the German climatic water balance for the period 1981–2010 (S1, Fig. 2E), and 3) the average number of lightning strikes (cloud to ground, CG) per km^2 in Germany for the period 1999–2018 (S1, Fig. 2F).

Naturally occurring fires are dependent on sites where the present vegetation provides sufficient biomass in a status allowing for ignition ("fuel", e.g. resinous needles, dry moss) under certain (e.g. dry and windy) weather and climate (prolonged periods of drought) conditions. This is especially the case for areas where continental and sub-continental pine forest communities (e.g. Leucobryo-Pinetum) constitute the PNV, on dry and sandy sites (Heinken 2007, 2008), as the abundance of Scots pine (*Pinus sylvestris* L.) is one of the key factors for forest fire occurrence in Central European forests (Adámek et al., 2015; 2016; San-Miguel-Ayanz et al., 2018; Müller, 2019). We identified all forest areas where Scots pine (*P. sylvestris*) constitutes a dominant tree species in the PNV dataset provided by the Federal Agency for Nature Conservation (Bundesamt für Naturschutz, 2003, Karte der Potentiellen Natürlichen Vegetation Deutschlands).

Since this study focused on natural disturbances only, we excluded factors responsible for human ignitions. We used the dataset "climatic water balance" during the forest fire season (DOY 60 until DOY 305) for the period 1981–2010 (Deutscher Wetterdienst, 2010) to identify areas with an average negative climatic water balance as a surrogate for drought potential. To assess the average annual number of lightning events per km^2, we used the dataset "Siemens Blitz Atlas" (www.siemens.com/blitzatlas). The dataset depicts the number of lightning events per administrative district and year for the period 1999–2018. We compared the average annual number of lightning events per km^2 with estimates of lightning ignition efficiency from the international literature. Here, we followed Latham and Williams (2001) who estimate that one CG lightning strike leads to 0.01–0.04 fires in wildland fuels in the United States of America. We caution that lightning ignition efficiency may vary across regions and that the "fuel type and fuel state play a much larger role than the lightning density in lightning fire ignitions" (Latham and Williams, 2001, p. 375). The three datasets were combined in ArcGIS 10.3 and resulted in a potential map (Fig. 2) of naturally occurring forest fires in Germany, namely the areas of the PNV dominated by Scots pine with a negative average climatic water balance and the average number of annual lightning events per km^2 (S1, Fig. 2D-F).

We used two other surrogate datasets to analyze the number and extent of actually occurring fires in Germany: The German forest fire risk index (Deutscher Wetterdienst, 2018) for the period 1981–2010 (S1, Fig. 2G) and the national forest fire statistics 2010–2018 (Federal Office for Agriculture and Food 2019). The German forest fire risk index is based on the Canadian fire weather index (Van Wagner, 1974) and was designed to assess the fire risk in German forests from March to October based on a variety of relevant environmental factors (Deutscher Wetterdienst, 2018). The German forest fire risk index distinguishes between five risk classes (very low – very high risk). We used a dataset of the German forest fire risk index that spatially depicted the average number of days per year with the two highest risk classes (high and very high risk) and overlaid it with our potential map of naturally occurring forest fires. The national forest fire statistics record the number and spatial extent (ha) of forest fires in a federal state for a given year and ignition factor. As some of the fires caused by natural ignition may not be distinguished from disturbances of anthropogenic origin, we evaluated the number and spatial extent (ha) per year (2010–2018) for two ignition factors: natural ignition and unknown source of ignition. We assumed that the number and extent of forest fires caused by natural events (CG lightning strikes) constitute the known minimum extent and number of natural forest fires in Germany; and in combination with the forest fires of unknown origin they depict the potential maximum number and extent of natural fires per year.

2.3.3. Landslides

We used the freely available pan-European landslide susceptibility map (ELSUS Version 2) with a spatial resolution of 200 × 200m to identify areas that are especially prone to landslides (Günther et al., 2014; Wilde et al., 2018; S1, Fig. 2B). The map was generated using a combination of information about landslide frequency ratios and a spatial multi-criteria evaluation model with the following predictors: slope angle, shallow subsurface lithology and land cover (Wilde et al., 2018). It distinguishes between five landslide susceptibility classes (very low – very high). For our analysis, we assessed the areas with very high landslide susceptibility as a case scenario. Since landslides are often triggered by heavy rain events (Guzzetti et al., 2008), we compared the areas identified with the geodataset "Grids of return periods of heavy precipitation (design precipitation) over Germany" (KOSTRA-DWD; DWD Climate Data Center, version 2010R; S1, Fig. 2C) with a spatial resolution of 8.15 × 8.20 km to identify the areas where very high landslide susceptibility and heavy rainfall events overlap. For the latter data set, we used pre-defined thresholds as case scenarios, that is a 100-year (50-, 30-, 20-year) return period with 72 h duration and a minimum precipitation depth of 107.2 mm per m^2.

2.4. Representativeness

First, we assessed the potential natural extent of areas affected by floods, forest fires and landslides in Germany and for each of the seven German ecoregions using geodata provided by the Federal Agency for Nature Conservation (BfN, 2012, Naturräume und Großlandschaften Deutschlands). Second, we investigated the potential extent of areas subject to floods,

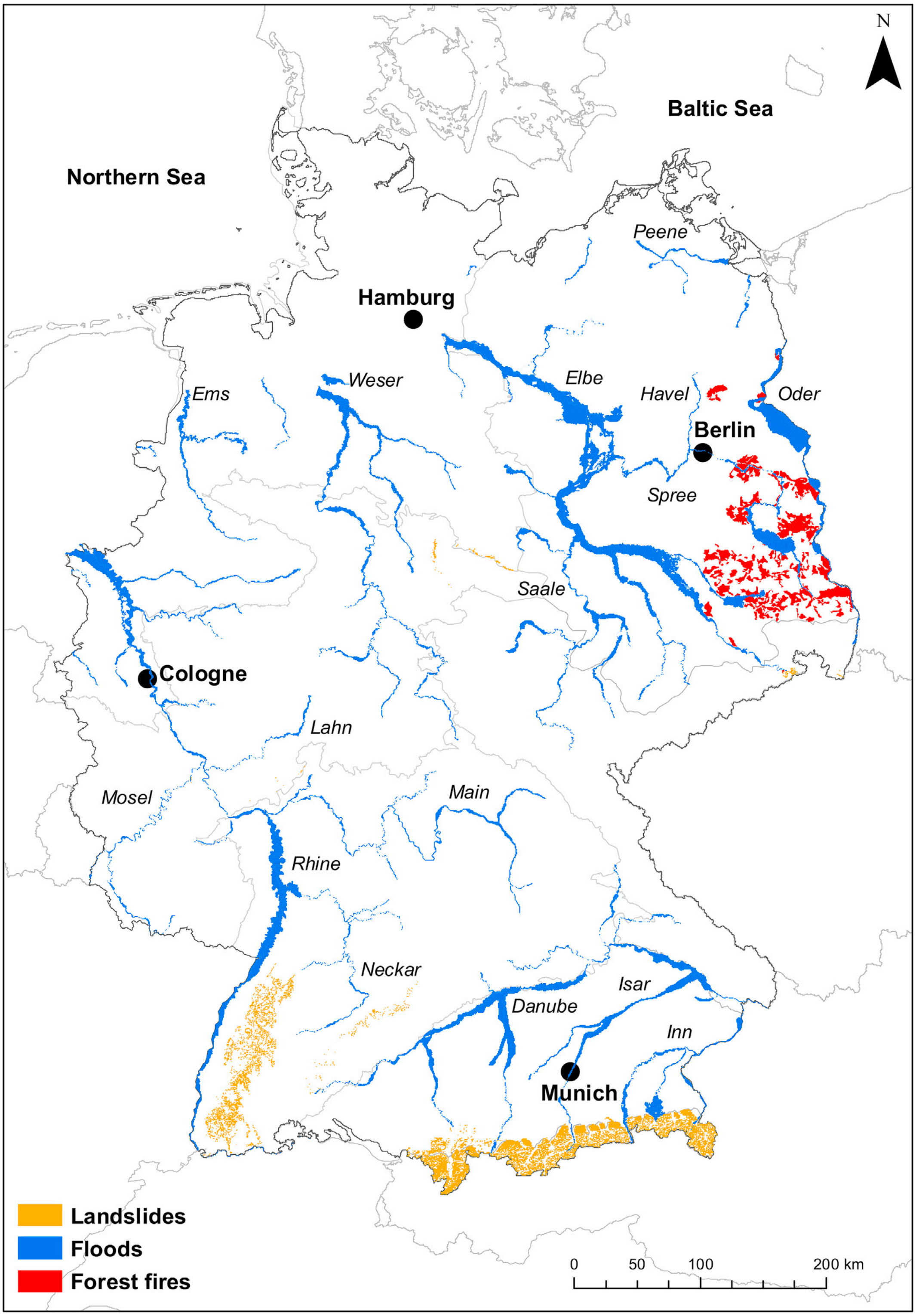

Fig. 2. The spatial potential for three natural disturbance types in Germany: Floods, forest fires and landslides (data on floodplains was provided by the Federal Agency for Nature Conservation, 2009, created using Geobasisdaten © GeoBasis-DE / BKG (2009)).

forest fires and landslides in existing National Parks and core zones of Biosphere Reserves to get an indication of how far the existing strict PAs already cover habitats dependent on natural disturbances. Following the wilderness and strict PA objectives of Germany and the EU, respectively, we argue that at least 2% (German wilderness goal) and 10% (EU objective for strict PA coverage) of the areas potentially subject to natural disturbances should be strictly protected. However, Schultze et al. (2014) argue that rare and threatened habitats require special consideration in SCP. Hence, we recommend that habitat types red-listed as threatened or rare ($\leq$1% of terrestrial territory; Rosenthal et al., 2015) are protected in higher proportions.

3. Results

3.1. Habitat types

We identified 19 habitat types that are dependent on one of the three selected natural disturbance types (Table 1). This represented 6.4% of all terrestrial habitat types assessed ($n = 295$). Fifty-two per cent ($n = 10$) of these 19 habitat types were listed as "critically endangered" (n = 1) or "endangered to critically endangered" (n = 9). Three habitat types (16%) were listed as "vulnerable to endangered". Only two were considered to be of "least concern". In contrast, 30% ($n = 83$) of the other terrestrial habitat types were considered "critically endangered" or "endangered to critically endangered".

3.2. River dynamics

The potential for river dynamics was calculated at 1,553,539 ha which equals 4.3% of the German terrestrial territory (Fig. 2; Supplementary material S2 Fig. S2). Within this scenario, 111,130 ha (0.3% of terrestrial territory) were covered by the river area and 461,214 ha (1.3%) were considered contiguous floodplain constituting the riparian zone that is still subject to river dynamics. Thus, the contiguous floodplain equals to 30% of the total area subject to river dynamics. Historic floodplains disconnected from river dynamics through dams and other anthropogenic infrastructure accounted for 981,195 ha (2.7%), which equals to 63% of the total spatial potential for river dynamics. Our calculated potential relative to the German terrestrial territory virtually met the spatial extent of the morphological floodplain calculated by Koenzen and Günther-Diringer (2009). Candidate sites for wilderness areas $\geq$500 ha in the contiguous floodplain accounted for 277,863 ha (0.8% of terrestrial territory) extending over 170 spatially separated sites. In addition, Harms et al. (2018) indicate that 189,206 ha of historic floodplain could be reconnected to river dynamics.

3.3. Forest fires

Our analysis indicated that Scots pine-dominated natural forests (PNV-type "continental pine-oak and pine forest") constitute the PNV on 314,862 ha of terrestrial land area, which equals to 0.9% of the German territory. The respective forest

Table 1
Habitat types with an obligate association to the natural disturbance types floods, landslides and fire; and their Red List status in Germany and more specifically in seven German ecoregions, based on Finck et al. (2017), Death and Barquín (2012), Zwick (1992), Benda et al. (2004), Simon and Rinaldi (2006), Brackhane and Reif (2018), Marston et al. (1995), Donath et al. (2006), Klimešová (1994), 1995, Barquín et al. (2012), Markus-Michalczyk (2020), Koch and Kollmann (2012), Virtanen et al. (2010), Stokes et al. (2011), Zackrisson (1977).

Habitat type	NW Low-lands	NE Low-lands	Western Uplands	Eastern Uplands	SW Uplands	Alpine Foothills	Alps	Red list-status in Germany[1]	Trend[2]	Reference
Natural and near-natural rhithrals	1	1	2	2	2	1	2	1-2	↓	Death & Barquín 2012
Natural and near natural potamals	1	2	1	2	1	1	-	1-2	→	Zwick 1992
Inland confluences	3	3	3	3	2	3	★	3-V	→	Benda et al. 2004
Sand bank	3	3	2	2	2	2	-	1-2	↓	Simon & Rinaldi 2006
Loam and loess banks	2	2	2	2	2	2	3	1-2	↓	Brackhane & Reif 2018
Sparsely vegetated area of gravel or rough gravel	2	2	2	2	1	1	2	1-2	↓	Brackhane & Reif 2018
Sparsely vegetated area of sand	2	2	2	2	2	2	-	1-2	↓	Marston et al. 1995
Flooded meadows	2	3	3	3	3	3	3	2-3	↓	Donath et al. 2006
Reed canary grass bed	3	★	★	★	★	★	★	★	→	Klimešová 1994, 1995
(Willow) scrub on floodplains	2	2	3	3	3	2	3	3-V	→	
Riparian alluvial forests of alder and ash	2	2	3	3	3	2	3	3-V	→	Barquín et al. 2012
Softwood alluvial forest	1	2	1	2	1	1	2	1-2	→	Brackhane & Reif 2018
Hardwood alluvial forest	1	1	1	1	1	1	-	1-2	→	Brackhane & Reif 2018
Tidal alluvial forest	1	-	-	-	-	-	-	1	→	Markus-Michalczyk 2020
Gravel area associated with waterbody of the subalpine to alpine zone	-	-	-	-	-	-	3	3-V	→	Koch & Kollmann 2012
Willow scrub on flood plains of the high montane to subalpine zone	-	-	-	-	-	-	2	2-3	→	Koch & Kollmann 2012
Natural and naturalized scree	2	2	3	3	3	3	★	2-3	↓	Virtanen et al. 2010
Balkan willow scrub	-	-	-	★	★	-	★	★	→	Stokes et al. 2011
Dry sandy pine forest	2	2	-	2	1	1	-	1-2	↓	Zackrisson 1977

[1]Red List-status in Germany: 0 = Collapsed; 1! = Critically endangered (acute); 1 = Critically endangered; 1–2 = Endangered to critically endangered; 2 = Endangered; 2–3 = Vulnerable to endangered; 3 = Vulnerable; 3-V = Near threatened (acute); ★ = No current risk of loss (least concern). [2]Current trend: ↓ = Decreasing; → = Stable. Blue: Habitat types associated to floods; Orange: Habitat types associated to landslides; Red: Habitat types associated to fire.

areas were restricted to the federal states of Brandenburg (75%) and Saxony (25%). These federal states were characterized by a distinct continental climate as shown, e.g., by a negative average climatic water balance of between −125 mm and −250 mm in the identified sites for the period 1981–2010. The average number of CG lightning strikes in the administrative districts comprising the identified sites ranged from 1.6 to 3.2 CG lightning strikes per km^2 annually (average: 2.5) for the period 1999–2018. In Brandenburg and Saxony, the number of CG lightning strikes peaks in June and July during the forest fire season (Siemens, 2020). Assuming 0.01–0.04 fires/CG lighting strike following Latham and Williams (2001), there would be 79–315 forest fires induced by lightning strikes per year in the identified sites. Consequently, we assumed that natural forest fires potentially can occur in all of the identified Scots pine-dominated natural forests.

The two surrogate datasets for actually occurring forest fires also indicated that natural forest fires play a role in the areas identified. In the federal state of Brandenburg, CG lightning strikes led to an average of 17 forest fires per year for the period 2010–2018, which burnt an average area of 4.1 ha annually. In Brandenburg, the causes of forest fires remained unknown in on average 101 cases that burnt 164 ha of forest area. In the federal state of Saxony, CG lightning strikes led to an average number of 4 forest fires per year for the same time period, which burnt 1 ha on average annually. In Saxony, the causes of forest fires remained unknown in on average 31 cases that burnt 5 ha of forest area. In the identified areas, the two highest warning levels of the forest fire risk index were reached on 43 days on average (max. 48 days, min. 34 days).

3.4. Landslides

The areas highly susceptible to landslides extended over an area of 382,469 ha, which equals to 1.1% of German terrestrial territory (Fig. 2, Fig. S2). They were exclusively situated in mountainous regions such as the Alps (69%), the Black Forest (27%), the Swabian Alps (1.8%), the Harz (1.4%), Saxon Switzerland-Eastern Ore Mountains (0.7%) and Taunus (0.2%). The mean precipitation for a heavy rain event with a 100-year return period with 72 h duration in the identified areas accounted for 191.5 mm (Range: 107.4–311.7 mm). This value decreased with shorter return periods, for example to 175.5 mm (50-year return period), 163.7 mm (30-year return period) and 154.3 mm (20-year return period).

3.5. Representativeness

The areas potentially subject to floods were mainly situated in the NE Lowlands (641,287 ha) and the Alpine Foothills (267,841 ha; Fig. 2). In contrast, areas with higher susceptibility to landslides prevailed in the Alps (232,062 ha) and the SW Central Uplands (109,831 ha). Sites prone to forest fires were almost exclusively located in the NE Lowlands (314,605 ha).

Habitat types subject to forest fires and floods were underrepresented in strict PAs: Only 0.15% of the areas potentially subject to naturally occurring forest fires and 0.81% of the areas potentially subject to river dynamics were covered by a National Park or the core zone of a Biosphere Reserve (Supplement S2). Overall, areas potentially subject to forest fires covered only 0.9% of the national terrestrial territory and the associated habitat type can thus be considered as rare in Germany. Regarding SCP, the areas with a higher susceptibility to landslides were within the range of German (2%) and European (10%) strict PA goals. Here, 6.8% of the areas were covered by a National Park or the core zone of a Biosphere Reserve.

4. Discussion

The spatial analysis conducted here identified the potential areas where selected natural disturbance types – floods, forest fires and landslides – could be expected in Germany under strict protection regimes. Our analysis indicated that habitat types shaped by these natural disturbance types are often endangered or critically endangered. Major causes are the suppression of abiotic natural disturbances in cultural landscapes and their underrepresentation in the current network of strict PAs. We found that the potential spatial extent of areas subject to the three investigated disturbance types is comparatively low, accounting for 6.3% of the German terrestrial territory. Yet, only few of these areas are currently covered by strict PAs. Particularly underrepresented are potential areas for naturally occurring forest fires and floods.

The methods and datasets used in our study have implications for future research. In our study we focused on large scale natural dynamics and used datasets with rather coarse spatial resolutions. Hence, natural disturbances occurring on smaller scales, e.g. floods in small- and medium-sized rivers, are not covered by our analysis but may already shape disturbance-dependent habitats in- and outside of protected areas. In addition, our research does not allow for specific statements about the magnitude and impact of attributes defining a natural disturbance regime such as frequency, seasonality, intensity and severity. Assessing the magnitude and impact of these attributes prior to major anthropogenic influences in Central European landscapes is hardly possible (Parsons, 2000; Brown et al., 2018). It may be more realistic to promote or reintroduce natural disturbances such as fire and flooding in novel regimes that benefit biodiversity (e.g. specific species and processes), and that are compatible with the constraints of the surrounding human-dominated landscape. Hence, our study may be the first step in investigating the role of natural disturbances for SCP in Germany. Future research can use the areas identified to investigate the potential ecological impact of natural disturbances on the local scale, where specific data can be generated and analyzed. Future research may also examine the role and interaction of other biotic and abiotic disturbance agents such as wind, avalanches, insect outbreaks and megaherbivores. In addition, more recent data and modelling could investigate the impact of climate change on natural disturbances in Central Europe (Sommerfeld et al., 2018). Seidl et al. (2017, p. 395), for example, concluded that “both ecosystems and society should be prepared for an increasingly disturbed future of forests”.

Promoting natural disturbances that are a potential risk to human safety or to economically relevant land use systems is a difficult task. Yet, the German government pursues the goal to set aside 2% of its terrestrial territory for strict protection, where accessibility for humans is limited and land use for economic purposes is excluded (Brackhane et al., 2019). In the following subsections, we discuss the implications of our finding with regard to SCP for a secondary wilderness in Germany and Central Europe.

4.1. River dynamics

Alluvium has always belonged to the preferred places for human settlement (Macklin and Lewin 2015). As a consequence, rivers and floodplains are among the ecosystems that are most heavily modified by human activities in industrialized countries (Meybeck, 2003), with negative implications for the related biodiversity (Poff et al., 1997). Most habitats depending on fluvial disturbance regimes are considered “endangered” or “critically endangered” in the German Red List of Threatened Habitat Types. Our research indicated that strict PAs comprising contiguous floodplains, where river dynamics could recur, were underrepresented or non-existent in some German ecoregions, e.g. in the Central Uplands. Consequently, the areas subject to river dynamics should be prioritized when designing future strict PAs in line with the German 2% wilderness goal. Yet, this is a difficult task in Germany and other Central European countries where river systems were modified through channelization, damming, groynes and hydropower plants (Harms et al., 2018; Schmitt et al., 2019), so that their natural, pre-transformation state is hardly identifiable (Brown et al., 2018). Harms et al. (2018) showed that 37% of the 79 largest rivers in Germany are dammed and 27% of the riparian zone is subject to constructional development, especially in the Central German Uplands. However, Harms et al. (2018) also estimated that 63% of the river segments analyzed have a high or very high potential for river restoration, especially in the German lowlands. For example, candidate sites for wilderness in the contiguous floodplain $\geq$500 ha would make up 102,171 ha (0.3% of German territory), notwithstanding a considerable additional potential which could be created in the historic floodplain through the relocation of dams. Since the restoration potential for large rivers is unevenly distributed among the ecoregions, it may be difficult to protect various threatened habitat types as strict PAs, e.g. because minimum sizes and morphodynamics cannot be reached. This includes sparsely vegetated area of gravel or rough gravel in the Central Uplands. In densely populated (eco-)regions with highly modified, dammed river systems, such as the Upper Rhine Region of the SW Uplands of Germany, river management will be necessary to initiate and control floods and river dynamics (Brackhane and Reif, 2018; Schmitt et al., 2019). Here, artificial channels and sophisticated flood control mechanism may allow for gravel transport and sedimentation, river bank mobilization and small-scaled, local morphodynamics to restore threatened habitats (Jeannot et al., 2019). Associated areas, however, depend on active management and thus do not coincide with wilderness criteria.

4.2. Forest fires

Our research indicated that fires need to be considered a natural disturbance type in pine-dominated forests in Brandenburg and Saxony. The PNV of the identified areas provides sufficient fuel for ground fires, the area is subject to lightning events to ignite fires; and recent fire statistics show that natural ignition indeed causes forest fires in this region. Hence, under natural conditions within strict PAs in the identified region, we assume that naturally ignited fires would occur. Müller (2019) hypothesizes that, given the amount of litterfall in the pine forests in the NE German Lowland, the intensity of ground fires would be moderate and not able to destroy mature *P. sylvestris*. Hence, these moderate ground fires would not negatively affect, but rather benefit endangered habitat types like Leucobryo-Pinetum (Walentowski et al., 2007; Heinken 2007, 2008), which would otherwise suffer from humus accumulation and eutrophication and finally be replaced by plant communities such as Quercion roboris or Luzulo-Fagion (Heinken, 2007, 2008; Ellenberg and Leuschner, 2010; Niklasson et al., 2010; Reinecke et al., 2014). Svenning (2002) and Schulze et al. (2018) argue that especially the interplay between fire and megaherbivores would lead to semi-open landscapes in Eastern Germany. Fires would have major implications for biodiversity conservation, as they would shape the habitat for fire-dependent, pyrophilic species such as, for example, the beetle *Melanophila acuminata* and other beetle species (Süda et al., 2009; Gutowski et al., 2020) or the plant *Arctostaphylos uva-ursi*. Our assumption may be supported by data on historical fire presence and current lighting ignition density in continental temperate forests of neighboring countries such as the Czech Republic, E Poland, W Belarus and S Sweden (Granström 1993; Niklasson et al., 2010; Adámek et al., 2015; Zin et al., 2015; Spînu et al., 2020). Under climate change scenarios, the areas subject to naturally occurring fires may increase in Germany and Central Europe and extend to other regions and countries (Schelhaas et al., 2010; Seidl et al., 2017).

In terms of implementing strict PAs subject to fire regimes, however, the reality is more complex. In Germany, forest fires are usually caused by anthropogenic factors and prevail on former military training sites with a high amount of ammunition distributed in the area (Ellwanger and Reiter, 2019). In Brandenburg, for example, areas contaminated by ammunition account for approximately 13% (2.9 mill ha) of the federal state’s territory. The (German Environment Agency, 2019) reports that 39% of all forest fires in Germany can be linked to anthropogenic causes such incendiarism and carelessness. Hence, on most areas subject to forest fires, German fire management deals with human induced events. Forest management integrating prescribed burning to lower fire severity, is conducted occasionally (Ellwanger and Reiter, 2019), but is currently not the standard for a country wide strategy. In Germany, extinguishing forest fires is the priority, for example to secure settlements adjacent to (former) military training areas. Fire suppression may lead to fuel accumulation resulting in catastrophic fires with substantial negative consequences (Parsons and DeBenedetti, 1979; Keane et al., 2002), especially in areas contaminated with ammunition. In 2019 in Brandenburg, for example, forest fires burnt 744 ha of Scots pine-dominated forests on a military training area near Jüterbog (Tagesspiegel, 2019).

We recommend that the influence of forest fires should be investigated further, not only in the regions identified, but also in regions where those disturbances could become abundant under climate change scenarios, both in Germany and in other Central European countries (Seidl et al., 2014). Associated studies could include the German drought monitor (Zink et al., 2016). Our analysis was largely based on the PNV map by Bohn et al. (2000). However, Chiarucci et al. (2010) argues that the role of fires may not be adequately addressed in the PNV mapping. Natural fires were most likely less frequent but longer in duration and larger in extent than now. Today they are mainly of anthropogenic origin, more frequent, but with less duration and extent (Chiarucci et al., 2010). Such characteristic of the shift from a natural to a cultural fire regime is also supported by empirical data from boreal Europe (Niklasson and Granström, 2000; Rolstad et al., 2017).

4.3. Landslides

Landslides usually cause a partial to complete change in biomass (Walker and Shiels, 2013), create habitat for early-successional species (e.g., Wiedermann et al., 2019), help to initiate patch dynamics (Baker, 1992), and were proven to increase habitat diversity, e.g. those associated with bare soils (Geertsema and Pojar, 2007; Tracz et al., 2019). Wildlife such as wild bees, with many species nowadays considered critically endangered in Central Europe and Germany, would benefit from landslides that provide habitat for nesting (Westrich, 1996), and potentially lead to more open habitat providing food resources. Implementing strict PAs in areas subject to landslides, and stopping mitigation measures, could help to restore dependent biodiversity, especially in mountainous regions where those disturbances are most prevalent (Wiedermann et al., 2019). In our study, we used the highest susceptibility class to identify areas most prone to landslides in Germany. Future studies may also incorporate lower susceptibility classes to approach other important criteria in SCP such as representativeness. In addition, it will be of uttermost importance to investigate local factors influencing landslide susceptibility and risk. These studies are crucial to develop sound PA management plans ensuring public safety and to inform visitor guidance management. In our study, we used datasets developed to depict the current susceptibility to landslides considering factors such as current land cover (Günther et al., 2014), in contrast to the potential natural vegetation (PNV) that can be expected under strict protection regimes (Bohn et al., 2000). Since both datasets suggest forests as the primary land cover type, we do not think that this potential bias will largely affect the conclusions drawn.

4.4. Implications for SCP and PA management

Our study revealed that areas potentially subject to the natural disturbance types floods and forest fires are underrepresented in strict PAs in Germany. In contrast, mountainous areas with very high susceptibility to landslides have a higher coverage by strict PAs. This is because in Germany, strict PAs tend to be situated in mountainous regions such as the Alps, whereas lowland areas such as the Alpine Foothills or the NW Lowlands, where intensive agriculture prevails, had little or no share of terrestrial strict PAs (Brackhane et al., 2019a). Terrestrial strict PAs of the lowland can be found in the less populated NE Plain, including the largest terrestrial National Park Müritz. The historic division of Germany (1945–1990) led to the establishment of a heavily secured inner-German border that finally became the so called ‘Green Belt’, featuring several Biosphere Reserves. In Germany generally, strict PAs were often designated in areas where it was politically and economically feasible rather than based on sophisticated concepts of SCP (Brackhane et al., 2019a).

In view of the 2% wilderness goal of the German government, (strict) PAs should be designed to include areas subject to natural disturbances to ensure the representation of all natural processes and habitat types prevailing in the country. Spatial prioritization should draw upon qualifying criteria for wilderness areas such as representativeness (Kukkala and Moilanen, 2013), connectivity (Brackhane et al., 2019a), naturalness, ruggedness, anthropogenic influence (Kuiters et al., 2013; Ceasu et al., 2015; Radford et al., 2019), habitat continuity and completeness (Schultze et al., 2014). “Completeness” can be defined as “the smallest area with a natural disturbance regime, which maintains internal re-colonization sources, and hence minimizes extinction” (Pickett and Thompson, 1978, p. 34). Defining the minimum area for a strict PA subject to natural disturbances will be necessary to meet the criterion “completeness” (Baker, 1992).

Our research indicated possible implementation and management dilemmas. Candidate sites for strict PAs in line with the German and European criteria may only be implemented in areas where disturbances as a part of local natural dynamics can actually occur and are not suppressed by human activities (e.g., fire fighting) or anthropogenic infrastructure (e.g., dams). That means for example, candidate sites in the historic floodplain, disconnected today from the river dynamics, are not “governed by natural processes” and consequently would not qualify as strict PAs as proposed by the European Commission (European Commission, 2020). Similarly, fire suppression in wilderness areas can be considered a major anthropogenic measure influencing natural dynamics in some of the identified pine-dominated regions in Brandenburg and Saxony. However, if active management is excluded in strict PAs, invasive neobiota such as *Fraxinus pennsylvanica* or *Acer negundo* could dominate forest stands in disturbance-dependent habitat types. Hence, the demand for future research is significant, and necessary for the successful implementation of strict PAs allowing for natural disturbances. Future studies may extend our analysis and investigate other factors determining natural disturbances within the areas identified such as frequency, intensity and severity; or include other abiotic natural disturbance types such as wind or avalanches. Tailored monitoring schemes can help to assess the *status quo* of candidate sites and the future development of wilderness areas subject to natural disturbances. Based on this information, candidate sites especially prone to invasive neobiota can be identified and avoided during the selection process. Monitoring schemes may also form the basis for the development of sophisticated PA management plans ensuring public safety and preventing potentially negative effects on adjacent cultural landscapes. In this context, other fields, such as flood and fire research and management (Parsons, 2000), need to be incorporated on the regional scale.

Moving from SCP to the implementation of strict PAs also requires concepts from the social sciences to reduce conflicts, e.g. with local stakeholders (Stoll-Kleemann, 2001). The German government plans to implement wilderness areas primarily on public lands, but has established a wilderness fund to support the acquisition of privately owned land, e.g. for meeting size requirements of wilderness areas (≥1,000 ha; Brackhane et al., 2019a, b). In addition, synergistic effects can be used to meet both, conservation and other land use objectives. For example, the implementation of strict PAs on land subject to floods can simultaneously support ecosystem-based flood control measures (Schindler et al., 2016). In 2017, the German government has initiated the “Blue Belt Initiative” aiming to re-naturalize so called secondary waterways, *inter alia* rivers that are no longer used for shipping. Here, dams could be removed and strict PAs could be implemented to protect and maintain floodplain ecosystems.

5. Conclusion

Natural disturbances caused by floods and forest fires are currently underrepresented in strict PAs in Germany. Current political goals to increase the extent of strict PAs in Germany and Europe bear the chance to incorporate areas subject to natural disturbances into SCP. Realizing the strict protection of such areas can help to restore disturbance-dependent habitats and associated species assemblages that are nowadays threatened. However, the need for further research is significant and should incorporate human safety concerns, invasive species and climate change. Protected area managers and land use planners should be prepared for an increase in disturbance events in the future under climate change.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.gecco.2020.e01436.

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