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Impacts and underlying factors of landscape-scale, historical disturbance of mountain forest identified using archival documents

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ABSTRACT

Large areas of temperate mountain Norway spruce (*Picea abies*) forests in Central Europe have been disturbed by windstorms and subsequent bark beetle (*Ips typographus*) outbreaks in recent years. The impact of these events has been severe, with millions of canopy trees dying in nature reserves, where salvage logging was not conducted. The occurrence of these windstorms has raised the question of whether such events were within the historical range of variability (HRV) of forest dynamics in Central Europe, where disturbances were traditionally perceived as non-natural and without strong relevance for forest development. To answer this question, we analyzed the available historical forest management maps documenting large-scale disturbance resulting from windthrow events in the years 1868–1870 in spruce- and beech- (*Fagus sylvatica*) dominated forests in the Bohemian Forest region (Šumava Mts., Czech Republic and Bayerischer Wald, Germany). We created a cross-boundary forest database covering 54 974 ha and containing information about tree species composition and age, and the severity of the 1868–1870 disturbance, considering the cumulative effect of the windthrow, subsequent bark beetle outbreak, and salvage logging. The age structure of the forests before the disturbances was unbalanced, with stands of 80–120 years underrepresented, and covering only 9% of the area, and stands older than 120 years, historically classified as old growth, covering 26% of the area. Within the decade that included the windstorms and their aftermath, 40% of the stands in the mountain range were at least partly disturbed, with significant effect on the oldest stands. To identify important factors responsible for the severity of disturbance, we constructed regression models relating severity to two groups of explanatory variables: forest stand characteristics and environmental attributes (mainly topographic factors). Overall, stand age was identified as the most important driver of disturbance severity across the landscape, with the oldest trees most susceptible. The high importance of age for disturbance severity showed the role of forest age structure in determining the scale of disturbances resulting from windstorms and associated bark beetle outbreaks. Nevertheless, despite the documented occurrence of frequent large disturbances during the two centuries that preceded the 1868–1870 events, old growth accounted for 26% of the area, making it clear that both large scale disturbance and old-growth forest are within the HRV of mountain spruce forest dynamics in Central Europe.

1. Introduction

Large areas of temperate Norway spruce (*Picea abies*) forests in mountain areas of Central Europe have recently been disturbed by several major windstorms: Vivian and Wiebke in 1990, Lothar in 1999, and Kyrill in 2007. Because windthrow in spruce stands usually triggers bark beetle (*Ips typographus*) outbreaks (Fischer et al., 2002; Wermelinger, 2004; Økland and Berryman, 2004), the wind-damaged forest areas subsequently suffered bark beetle infestations. These infestations resulted in thousands of hectares of canopy trees dying in nature reserves, in which sanitary logging was not performed (Lausch et al., 2011). Until recently, such large disturbances were not thought to be a natural part of mountain spruce forest dynamics in Central Europe (Splechtna et al., 2005). These events raised two basic questions: (1) whether these large disturbances were within the historical range of variability (HRV) of forest dynamics in Central Europe; and (2) what future effects these disturbances will have on forests. Knowledge about HRV

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could help us better understand the long-term dynamics of these mountain forests and therefore shape current management and nature protection strategies in the area (Landres et al., 1999; Keane et al., 2009).

Various kinds of disturbances, including stand-replacing events operating at the landscape scale, are among the main natural forces shaping forest structure and dynamics around the world (Pickett and White, 1985; Frelich, 2002; Gromtsev, 2002; Turner, 2010). Although severe wind disturbances are considered to be the natural, and even dominant driver of some temperate forest dynamics in North America (Canham and Loucks, 1984; Frelich and Lorimer, 1991), their natural role in temperate forests of Europe is still relatively unknown (Wolf et al., 2004; Nagel and Diaci, 2006; Nagel et al., 2006; Zielonka et al., 2010; Panayotov et al., 2011). They have also been revealed to be an important, although not dominant, feature of the disturbance regime of boreal coniferous forests (Ulanova, 2000; Rich et al., 2007).

In Europe, over the period 1950–2000, storms caused more than 50% of the damage attributed to all disturbance factors, with most of the storm damage reported from mountain areas of Sub-Atlantic and Central Europe (Schelhaas et al., 2003). Despite such a large amount of forest affected by wind disturbance, this phenomenon, along with other large-scale stand-replacing disturbances such as fire and insect outbreaks, was long thought of as non-natural in Central Europe and without strong relevance for forest development (Clark and Merkt, 1989; Ellenberg, 1996). In Europe, forest dynamics for a long time have been shaped largely by human activities (Glatzel, 1999). Therefore, the many large-scale disturbances as well as the overall increase in disturbance frequency over the last century have been ascribed mainly to management-driven changes in forest species composition and structure (Seidl et al., 2011). Additionally, Central European traditional forestry schools have emphasized the influence of site-specific conditions on vegetation patterns. Thus, small-scale gap dynamics were long thought to be the only type of disturbance influencing forest structure, with large-scale or intensive events not considered to be a natural part of forest dynamics (Falinski and Falinska, 1986; Korpel', 1995; Splechtna et al., 2005). Although large-scale disturbances eventually came to be accepted as part of the natural dynamics of various forest types in this region (Heurich and Jehl, 2000; Kulakowski and Bebi, 2004; Svoboda and Pouska, 2008; Svoboda et al., 2010; Panayotov et al., 2011), we still largely lack understanding of natural disturbance dynamics in the Central European context. In particular, we lack the knowledge of the interactions between disturbances and particular forest state and environmental factors necessary to validly assess HRV. Indeed, the effects of a storm event may vary greatly across the landscape and depend on the interaction of wind characteristics and environmental conditions that include forest species composition (Papaik and Canham, 2006), spatial/age structure, soil condition, and land surface parameters (Ruel, 2000; Achim et al., 2005; Scott and Mitchell, 2005).

The paucity of knowledge of long-term natural landscape dynamics could be addressed by space-for-time substitution (Hessburg et al., 1999), modeling (Seidl et al., 2010) or the use of archives. However, the use of space-for-time substitution is limited both by the extent of natural forest in a given region and by the variability of environmental conditions across large areas (Keane et al., 2009). Models also face obstacles, as they are difficult to parameterize precisely, and require spatially explicit data for initialization and validation. Thus, the most valuable source of information on disturbance regimes can be found in natural and documentary archives (Swetnam et al., 1999). Natural archives such as tree rings (Zielonka et al., 2010; Hadley and Knapp, 2011; Svoboda et al., 2012; Čada et al., 2013) and pollen records (Nielsen and Odgaard, 2005, 2010; Hernández et al., 2011) enable relatively precise assessment of past disturbance regimes, although obtaining landscape-scale results requires intensive, time-demanding field sampling and laboratory analyses.

In areas long used by humans, historical maps and records offer comprehensive sources of information on forest development and human impacts at the landscape scale (Brůna et al., 2010). Modern forestry in Central Europe, based on the German tradition, has employed thorough maps (Fernow, 1911) and accompanying written documents (Pretzsch, 2009) that include detailed information allowing retrospective examination of woodland development over the last ca. 200 years (Axelsson et al., 2002; Wulf et al., 2009; Šebková et al., 2011; Mikusinska et al., 2012). Despite the recognized importance of historical maps as a source of spatially explicit data on forest structure and species composition, however, they have only rarely been used for information on historical disturbances (Keane et al., 2009).

Here we employ available historical sources of information on forest management and disturbance to assess the landscape-level effects of late 19th century, severe, large-scale disturbance events on Norway spruce-, beech- (*Fagus sylvatica*), and fir- (*Abies alba*) dominated forest (Heurich and Englmaier, 2010) of a Central European mountain region. The high representation of old-growth forest in the study area that was present prior to a series of severe disturbances in 1868–1870, as documented in the archives, enabled us to gain a better understanding of landscape-scale disturbance dynamics and the factors that influence disturbance severity in both natural and managed forests.

Our particular goals are to: (i) assess age structure and species composition at the landscape scale, using available historical data from before 1868 on about 54 000 ha of forest; (ii) analyze the impacts on the forests stands of the 1868–1870 windstorms, subsequent bark beetle outbreak and salvage logging, in terms of area and type of stands affected by disturbance; and (iii) identify the factors that affected the spatial distribution and severity of disturbance, and use them for modeling disturbance at the landscape scale.

2. Materials and methods

2.1. Site and historical archive descriptions

The Bohemian Forest region (Fig. 1) comprises a 190 km long, heavily forested mountain range on the borders of Germany (Bayerischer Wald), Austria (Böhmer Wald) and the Czech Republic (Šumava Mts.), with heights of 600–1450 m a.s.l. and a northwest/southeast orientation. Geologically, this range is among the oldest in Central Europe, with typical relict plateaus having elevations higher than 1000 m a.s.l. The lower elevations in this area would naturally be covered by mixed montane forest of beech, fir and Norway spruce, which could be placed mainly in two phytosociological associations: *Luzulo-Fagetum* at lower elevations, and *Calamagrostio villosae-Fagetum* at middle and higher elevations (Neuhäuslová, 2001; Fischer et al., 2013). However, the mixed montane forests have largely been replaced by Norway spruce plantations, especially on the northeast, Czech side of the mountain range. The highest elevations are covered by pure Norway spruce woodland (*Calamagrostio villosae-Picetum*), with Norway spruce also dominating waterlogged areas that feature sphagnum-rich (*Sphagno-Picetum*) and moss-rich (*Bazzanio-Picetum*) phytosociological associations (Neuhäuslová, 2001; Fischer et al., 2013). The vegetation on south- and southwest-facing slopes includes sycamore maple (*Acer pseudoplatanus* L.), Norway maple (*Acer platanoides L.*), mountain elm (*Ulmus glabra Huds.*), large-leaved linden (*Tilia platyphyllos Scop.*), and common ash (*Fraxinus excelsior* L.) as subordinate species (Ewald et al., 2011). Two na-

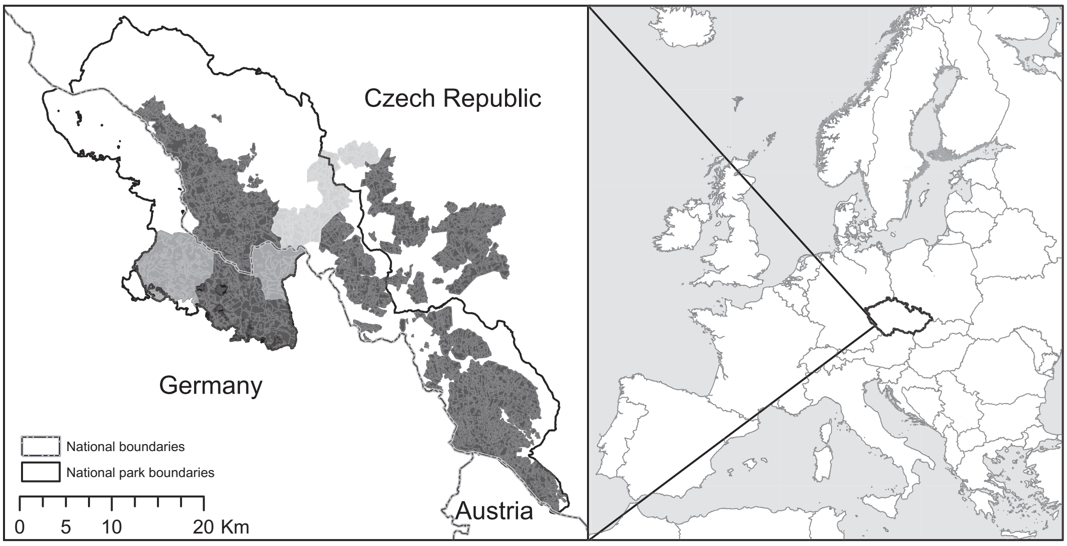

Fig. 1. Map of the area with national park borders (black lines). Area with all historical data available covers 43 247 ha (dark grey), additional 6983 ha does not contain sufficient data about age structure (grey) and 4774 ha does not contain sufficient data about disturbances in 1868–1870 (light grey). Total area with species composition data covers 54 974 ha of forests.

tional parks were established to protect this forested region: Bohemian Forest (in 1991) and Bavarian Forest (in 1970), on the Czech and German sides of the border, respectively (Fig. 1). In our study we focused mainly on the area of these two national parks.

In the 19th century, when the focal wind events of our study occurred, the area's various landowners were all using similar silvicultural practices derived from the then common Central European/German approach to forestry (Martin, 1906). These extreme wind events occurred in the winters of 1868 (December 7–8 and 24–26), 1869 (November 1–3, 14 and 15), and 1870 (October 26–27), resulting in large-scale windthrow disturbance and subsequent bark beetle outbreaks. The cumulative impact of windthrow, bark beetle outbreak, and salvage logging was well documented during the approximately 10 years that the disturbed stands were managed after the windstorms. In fact, this was the first large-scale disturbance in the area for which we have localization and disturbance severity records, as the previous events were documented only in terms of amount of timber losses (Elling et al., 1987; Jelínek, 1988).

The historical forest maps used in this study include information about the borders, dominant age class, and species composition (in terms of presence of important tree species, but not prevalence) of each stand. The positional accuracy of the old forestry maps is very high, since they were created using sophisticated cadaster mapping methods (Kačmar et al. 2013), and most of the stand borders are still used in present forest management maps. For the Czech part, they were compiled by Jelínek (2005) from multiple archives. Complementing the maps of the Czech areas were forest management books that have more detailed information about every stand. For the German part, we used forest inventory maps from 1844, 1856, and 1860 covering different parts of the area, as well as a species composition map constructed by Elling et al. (1987) based on historical data.

Importantly, both Elling et al. (1987) and Jelínek (2005) constructed maps of disturbance severity, covering approximately the decade following the 1868–1870 windstorms. The information used in these maps was originally recorded because, during this decade, stand management was dictated by disturbance impact. Therefore, these maps documented the cumulative severity of disturbance from the windthrow and subsequent beetle outbreaks and salvage logging. We presume that, due to the scale of the disturbance, most management activities (and therefore documentation) done following the 1868–1870 wind events were concentrated in or near the areas subjected to this disturbance, although this was not specifically stated in the documents.

The Czech forest management books recorded summary amounts of salvaged wood from each stand or area. Jelínek (2005) translated these salvaged wood records into disturbance severity data, classified in three roughly quantitative categories: low, consisting of damage to single trees; intermediate, indicating damage to approximately half the trees; and high, for stand-replacing events in which all canopy trees in a given stand were damaged. Jelínek (2005) also grouped the stand ages in six classes: 0–40 years, 40–80 years, 80–120 years, more than 120 years, self-regenerating logged class (R, 20% mature trees left for regeneration), and naturally sparse forest class (S). The oldest age category, encompassing stands over 120 years old, represents the definition used by historical foresters for old-growth stands, i.e., those without significant past human influence (Jelínek, 1988). We assessed the categorical accuracy of the age class designation used by Jelínek (2005) by comparing it with detailed stand information from the forest management books and maps for random locations, with reasonable results. The high accuracy was facilitated by the usage of Jelínek (2005) age classes that were broader than those in the original forest maps.

Using ArcMap 10.0 (ESRI, 2011), the historical forestry maps from both sides of the border were digitized and combined, resulting in a cross-boundary map covering 54 974 ha of the two national parks. The legend of the forest maps of both national parks was unified regarding both the disturbance severity and age structure, in both cases using the classifications developed by Jelínek (2005). Because some forest records are missing, the age structure of some parts of the Bavarian Forest NP and historical disturbance information from the Zdíkov estate (Bohemian Forest NP) remains unknown. These areas were therefore omitted from the age structure and historical analyses, respectively (Fig. 1).

2.2. Modeling the disturbance

To identify important local attributes responsible for disturbance severity, we constructed a regression model (the "all variable model") with disturbance severity as a dependent variable and two groups of explanatory variables: forest stand characteristics and environmental, mainly topographically derived factors (all listed in Table 3). These were all assessed per point in a grid with 1.25 km spacing to minimize autocorrelation of variables used in the model. The spatial independence of explanatory variables was tested by Moran's *I* test in R 2.14.2 (R Development Core Team, 2012) as implemented by Bivand et al. (2012). The self-regenerating logged and naturally sparse forest areas, as well as areas without sufficient information on age structure or disturbances, were excluded from this analysis.

Severity of disturbance at the sampled point was calculated as the mean disturbance severity in a circle of 250 m radius, thus including the surroundings while avoiding the arbitrary nature of stand borders. This number was converted to a proportion (0–1) for use in a generalized linear regression with binomial distribution and logit link function assuming single tree damage (causing immediate or eventual tree death) to represent 10% disturbance severity, damage to half the trees to represent 50% severity, and damage to all trees to represent 100% severity.

The stand characteristics tested included age, Euclidean distance to stand edge for each different age class, and the presence/absence of each major tree species. Age was computed as the mean age class in a circle of 250 m radius (as a surrogate for forest stand), and we then calculated the difference in mean age class between the 250 m circle and a 500 m circle to yield the age difference index value. Similar index was used in Mikita et al. (2012) to identify forest edge areas susceptible to wind damage due to heights differences. We used this approach instead of stand data because there was not only variability in sizes among stands, but also in disturbance within some stands, resulting in multiple stand parts with different disturbance data.

A digital elevation model based on ASTER Global Digital Elevation Model V002 (METI/NASA, 2011) was used to calculate values of topographic variables related to wind risk and site conditions. The morphometric protection index, equivalent to the positive openness described in Yokoyama et al. (2002), and similar to the distance-limited Topex (Pyatt et al., 1969) widely used in windthrow risk prediction and modeling (Quine and White, 1998; Hanewinkel et al., 2004, 2011; Scott and Mitchell, 2005), was computed in SAGA GIS (SAGA Development Team, 2011), along with slope, aspect, and sky view factor. MAXTOPEX was calculated following the method of Mikita et al. (2012), who used it in the same area to model the recent disturbances. Other commonly used site-descriptive indexes, including SAGA wetness, solar radiation, terrain ruggedness (TRI), relative height and slope position, altitude above channel network, and effective air flow heights from eight principal directions were calculated using SAGA GIS. All stand-related variables were calculated and all DEM-related layer values and latitude and longitude were extracted using ArcMap 10.0 (ESRI, 2011). Point selection, variable testing, modeling, and validation were done using R 2.14.2 (R Development Core Team, 2012). Significant variables and all reasonable interactions for the model were selected by backward and forward selection based on the Akaike Information Criterion (AIC). To assess the usefulness of historical data for modeling the effect of disturbance, we validated the model on a set of points in the same design as the original, but shifted from it both latitudinally and longitudinally by half the distance between the points (625 m), thus covering a similar area and gradients.

3. Results

3.1. Age structure

Age structure of the 47926 ha of forests before the 1868–1870 disturbances was unbalanced, with most stands either younger than 40 years (33%) or 40–80 years old (25%). The 80–120 year age class was present in only 10% of the area and 26% of the forest belonged to the age class comprising stands older than 120 years (Fig. 2).

The large-scale disturbances of 1868–1870 substantially altered the age structure. The older classes were subject to substantially greater disturbance, resulting in decrease of the area of forest older than 120 years (old-growth forest) by 69% and those of age 80–120 years by 55%. In the oldest age class, the windthrow

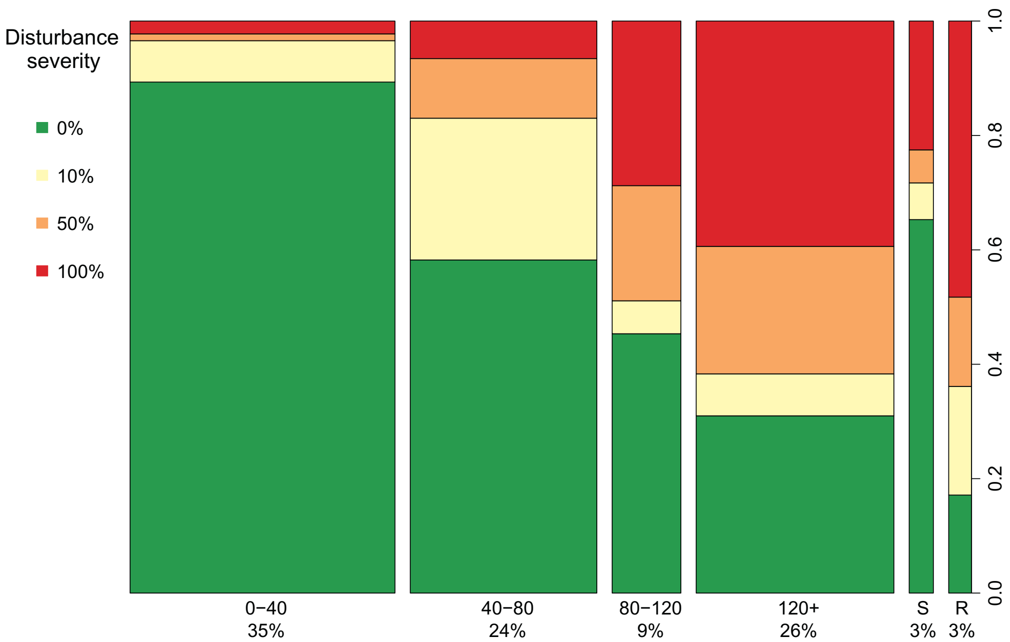

Fig. 2. Disturbance severity significantly increases in older age classes. More of the younger age stands were managed before the disturbance. Width shows proportion of total area. "S" means sparse forests and "R" means areas left intentionally for natural regeneration (20% of standing trees left after logging).

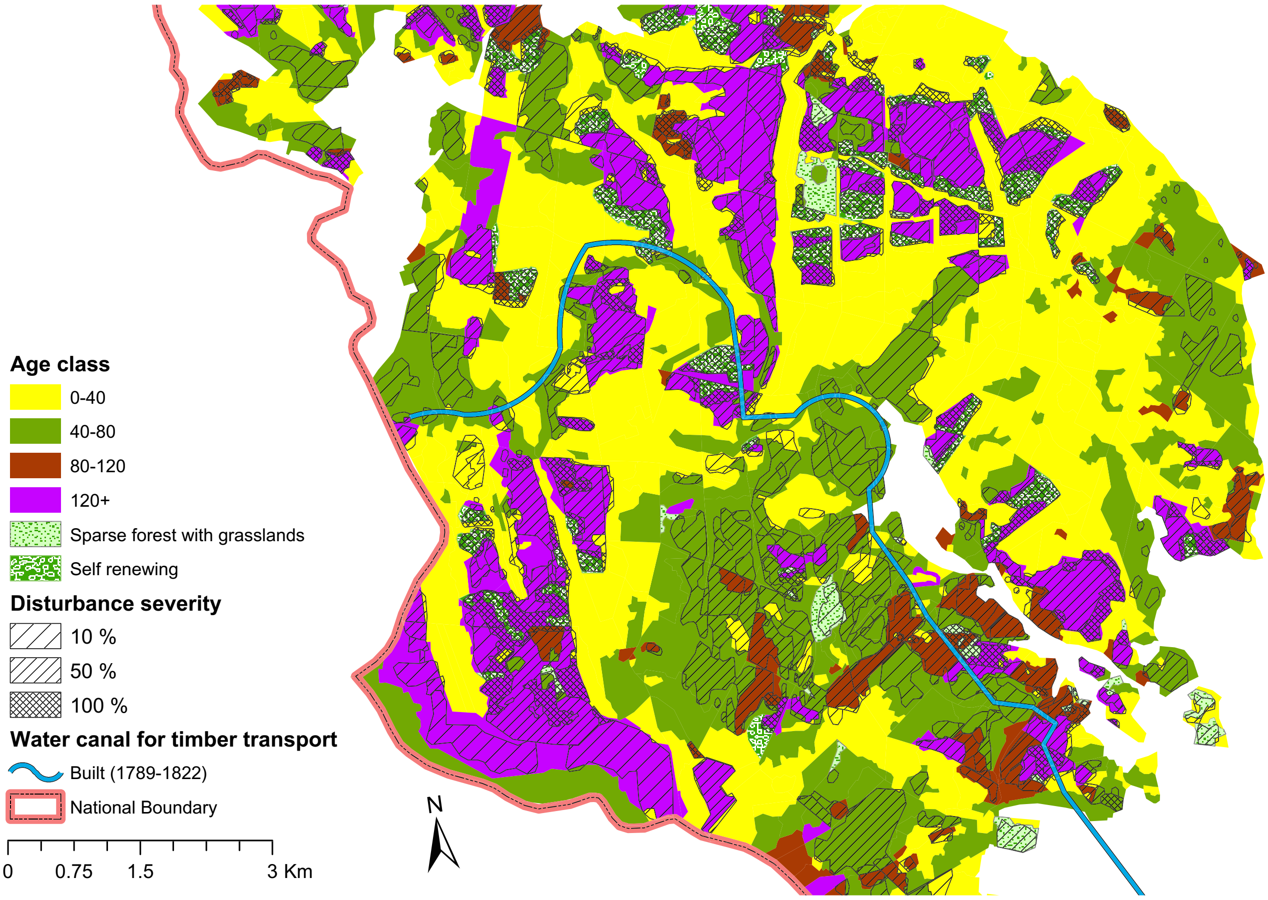

Fig. 3. Detailed map of the Trojmezná region. Almost all areas of primeval forest were disturbed to some degree, although not necessarily completely. The nearby areas were surrounded by intensively managed areas before the 1870 disturbance, partly enabled by a canal that had been constructed several decades earlier, which enabled logs to be transported from the mountains. The canal also made salvage logging possible after the 1870 disturbance, unlike for previous disturbances. Map is an overlay of data published by Jelínek (2005).

disturbance and subsequent bark beetle infestation and salvage logging resulted in the greatest proportion (41%) of stands experiencing loss of all trees, whereas in younger stands, this level of destruction was much rarer (2% for age class 0–40 years and 7% for 40–80). In the two youngest classes of stands, the most common level of disturbance was the loss of individual trees or half of the stands. Most (83%) of the forest area belonging to class R (logged with 20% of trees left for natural regeneration) was at least partly disturbed, in contrast with those of class S (naturally sparse forests), of which only 35% of their area showed disturbance.

From the analyzed area of 43 247 ha, 7725 ha of stands were completely damaged (100% of canopy removed), 4647 ha had half the canopy removed, and 5014 ha had individual trees that were damaged, resulting in 40% of the stands in the study area being at least partly disturbed within approximately a single decade. Of the oldest, unmanaged forests, only 31% were left undisturbed, meaning that the old-growth forests decreased from 26% (11 177 ha) to just 8% (3464 ha) of the analyzed area. This is most apparent in the Trojmezná region, where almost all the stands older than 80 years were disturbed to some degree (Fig. 3).

3.2. Tree species composition

Spruce was present in 90% of stands. Pure spruce stands accounted for 46% of stands, forming the most common forest type, followed by the mixture of spruce, beech and fir, which covered 34% of the area. Fir was present in 41% of the stands and beech in 37% of the stands, mainly in the southeastern part of the area (Table 1). Species composition changed along an elevation gradient (Fig. 4, Fig. 7), with higher elevations having increasing proportions of pure spruce stands and decreasing proportion of beech and fir. In pure spruce stands, the two youngest age classes prevail, whereas mixed stands had more balanced proportions of age classes dominated only slightly by the oldest one.

Pure spruce forest was the most disturbed, with 62% of its area affected by the disturbances (Table 1). Similarly, about 58% of the second most common forest type, mixed spruce, beech and fir was affected, but the proportion of stands completely destroyed was lower (21%) than in pure spruce stands (33%), and these mixed stands were more affected by single tree disturbance (19%), than were the pure spruce (11%) stands (Table 1). Disturbance severity was low in the beech-dominated and mixed spruce and beech stands, which represented a small proportion of the landscape (<5%). The species composition in the disturbed area and in the unaffected area was very similar (Fig. 4), although disturbance extent differed among species groups along the elevation gradient (Fig. 4 and Fig. 8).

3.3. Modeling the disturbances

Mean age was identified as the most important factor for disturbance severity, with a positive effect. Latitude had a positive influence, indicating more severe disturbance in northern areas. Disturbance was significantly more severe on the Czech side of the border (i.e. northeastern slopes) than the German. In the validation, the all variable model performed quite well for the Czech

Table 1
Disturbance severity distribution among species in relative procents, with tree species proportions before the disturbance, calculated using total area of stands that had the species recorded as present.

Species	Disturbance Severity				Proportion of forest stands before (%)
	0%	10%	50%	100%	
Spruce	38	11	18	33	46
Spruce + beech + fir	42	19	19	21	32
Spruce + fir	57	14	13	16	8
Spruce + beech	68	12	12	7	4
Beech + fir	57	10	14	19	2
Beech	78	17	4	1	<1
Fir	50	30	14	6	<1
Other	65	7	6	22	8
Total	44	13	17	26	100

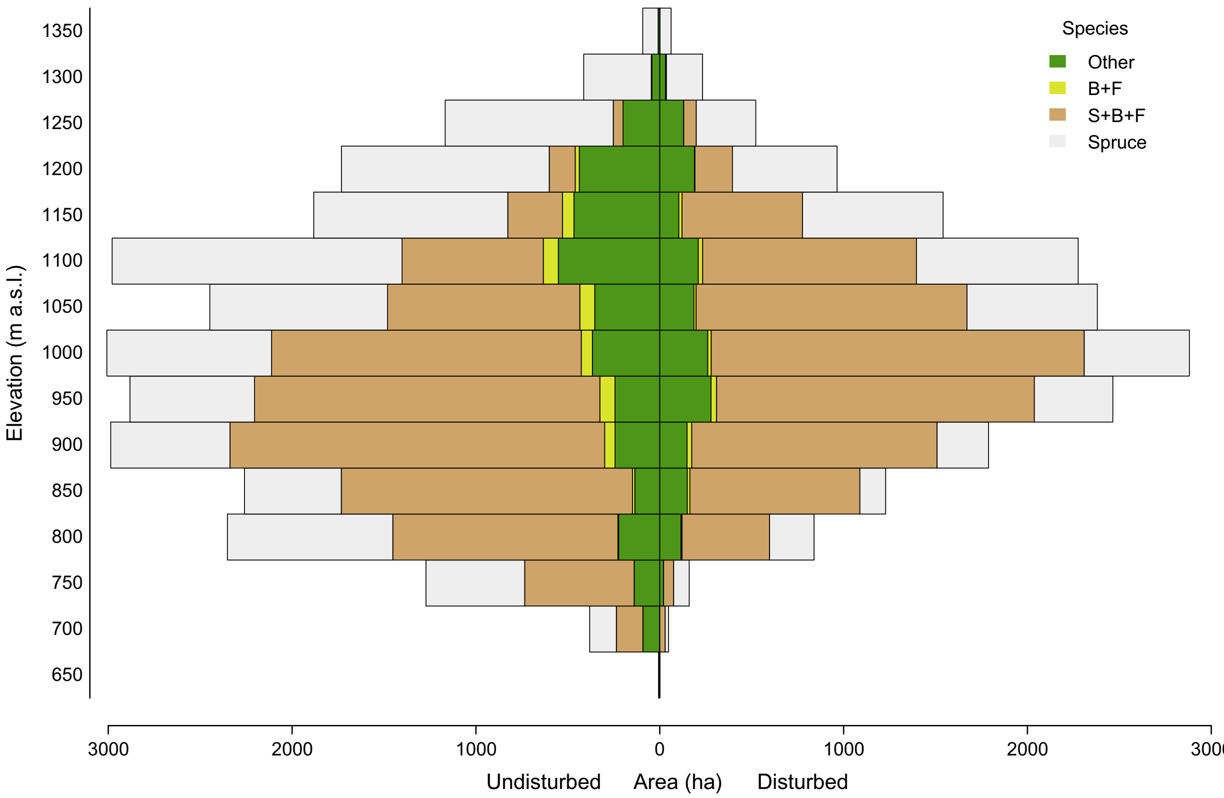

Fig. 4. Tree species composition for disturbed and undisturbed areas along the elevation gradient shows increasing proportions of spruce dominated stands and decreasing proportions of beech and fir with increasing elevation. F = fir, B = beech, S = spruce.

area, but failed to predict small-scale disturbances for the German area.

Therefore, a model with only Czech data was also developed (the "Czech territory model", Table 2), in which both mean age class and latitude were significant. There were insufficient data points to create a separate model for the German side. No topographic variable or its interaction with other potential explanatory variables was identified to be significant for the disturbances in either of the models; therefore, we created a third model without any age-related variables or country designation (the "environmental variable model") and ran the same parameter selection. This model identified mean elevation in a 250 m circle and effective air flow heights (Boehner and Conrad, 2008) from constant wind direction of 90° as the most important variables (Table 2).

Two separate models tested the responses to disturbances of the two types of stands with the most common species composition (pure spruce and mixed). In the "pure spruce stands model", age was found to be the most important factor, followed by latitude and longitude. No significant role of elevation was identified for these stands, in contrast to the "mixed stand model" (spruce, beech and fir), which responded to age, elevation, and effective air flow heights (Table 2 and Fig. 8).

Elevation was a significant explanatory variable in some of the models ("environmental variable model" and "mixed stands model"). However, the separate analysis of disturbance severity along the elevation gradient revealed that, overall, the proportion of disturbed forests increased with elevation up to 1000–1150 m and then started to decrease slightly (Fig. 5). Nevertheless, we have to consider that the area of forests at the highest elevations was much smaller than those of other elevations, and this could have distorted the results.

The spatial pattern of disturbance predicted by the all variable model for all data points was highly similar to the observed disturbance across the landscape (Fig. 6). The validation showed a close fit with this model, with a Pearson correlation coefficient of 0.723 between the predicted and observed values, indicating high predic-

Table 2
Parameters, slopes and significances of the five types of model applied. Independent variables were standardized. The “environmental variable model” did not include any age related variables. “Pure spruce model” and “mixed stands model” were used only for points on which the appropriate species were present (spruce; and spruce, beech, fir, respectively). Significance codes: ‘×’ not tested in the analysis, ‘–’ removed during selection, ‘***’ < 0.001,‘*’ < 0.05. Variables not significant in any analyses are not included.

	All variable model		Czech territory model		Environmental variable model		Pure spruce stands model		Mixed stands model	
Mean age in 250 m circle	3.41	***	3.30	***		×	3.13	***	3.67	***
Lattitude	0.97	*	0.97	*		–	1.70	*		–
Longitude							3.19	*		–
Country (GER)	−3.11	***		×		×				
Mean elevation in 250 m circle		–		–	11.42	***		–	16.49	**
Effective air flow heights		–		–	−5.60	***		–	−8.31	**
AIC	152.87		145.35		218.47		57.51		57.52	
n	254		217		254		94		96	

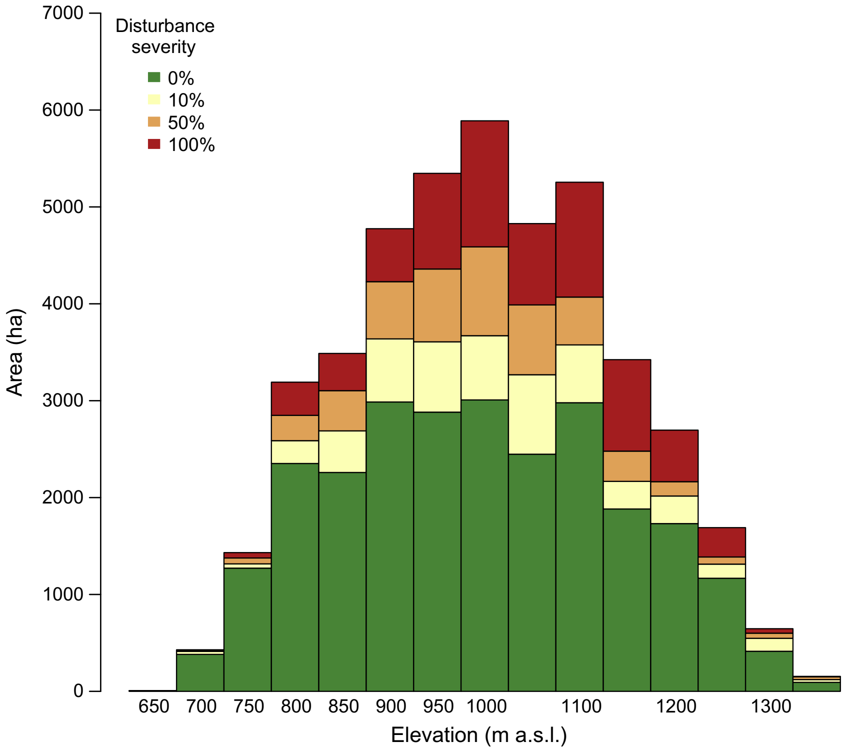

Fig. 5. Severity of disturbance along the elevation gradient (in 50 m intervals). From the relative proportions of disturbance severity categories, it can be seen that the highest severity of disturbance was between 1000 and 1150 m, the elevation range with the greatest stand area.

tive power of the model. The Czech model showed similar power, with a Pearson correlation coefficient of 0.704. The model based only on environmental variables had only a 0.373 Pearson correlation coefficient. The validity of the two models based on the most common species compositions (pure spruce and mixed stands) was not tested.

4. Discussion

4.1. Age structure and HRV

Our study showed significant changes in the age structure in the studied landscape as a result of the severe disturbance. The fact that the oldest stands experienced the highest severity disturbance (Fig. 2), leaving only 31% of their pre-disturbance extent – which had been about 26% of the area – had severe consequences for the forest on a landscape scale. This suggests that the temporal pattern of high severity disturbances probably strongly influences the proportions of forest in late successional stages.

Moreover, there is evidence of numerous previous large-scale, high-severity windstorms damaging forests in the region (Elling et al. 1987; Zatloukal 1998 and Brázdil et al. 2004), including major windstorms in 1710, 1740, 1778, 1810s, 1820s, and 1830s, most of them followed by bark beetle outbreaks. Historical documents state that the windstorms of 1710, 1740, and the 1830s disturbed large areas of forest, which was confirmed by dendrochronological analyses from two localities in the area, Trojmezná and Jezerní Hora (Svoboda et al., 2012; Čada et al., 2013). However, the precise geographical extent of the disturbance caused by any of these events is not known.

Despite the documented earlier frequent occurrence of large disturbances, the oldest class at the onset of the 1868–1870 event covered 26% of the forest area. However, if such disturbances were frequent enough, the forest would rarely naturally reach the oldest stage and so-called old-growth character.

Taken together, the high representation of old-growth forest prior to the 1868–1870 disturbance and the presence (at the highest elevations) of early successional stages that resulted from

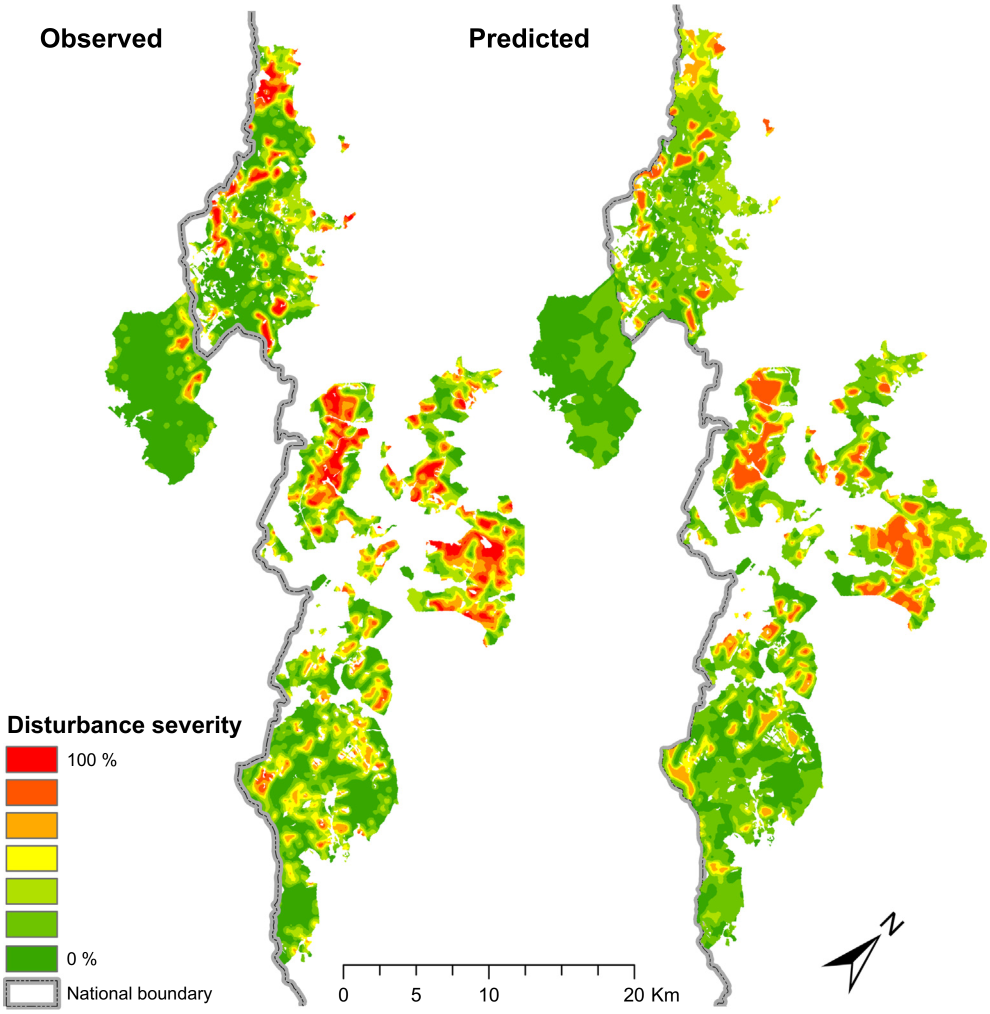

Fig. 6. Visual validation of the all variable model. Observed disturbance severity (left) and predicted disturbance severity (right) show similar patterns, although the observed is more detailed and has greater contrasts.

earlier disturbances indicate that both stand-replacing disturbances and old-growth belong to the HRV of mountain Norway spruce- and beech-dominated forests. Thus, the forest could be characterized as a landscape mosaic of old-growth and earlier successional stands.

We must consider to what extent the forest dynamics reflected management activities conducted before the study period. Up until the very late 18th century, there had been no intensive logging activities in the region, due to its low population and relative inaccessibility. Indeed, in the second half of the 18th century, this area represented one of the largest remnants of natural forest in Central Europe (Wild et al., 2004). However, canals for timber transport were built from just before the end of the 18th century until the first half of the 19th century, and they facilitated more intensive forestry logging operations by enabling logs transport from the mountains. This resulted in many new forest edges in previously homogenous areas, leaving old stands isolated and sensitive to disturbance (Fig. 3). Together with the occurrence of earlier severe disturbances (Brázdil et al., 2004), this influenced the age structure before the studied large-scale disturbance of 1868–1870. Indeed, in 1868, immediately prior to the studied disturbance, some forests had already been logged, and in combination with previous disturbances, this could have caused the relatively low representation of the 80–120 year class. However, many stands were managed for the first time only after the studied 1868–1870 disturbances (and not necessarily intensively), and therefore we could still consider this area to have been an especially large exception to the intensively managed Central European forest landscape (Glatzel, 1999), suitable for calibration of the HRV concept.

4.2. Tree species composition

Both of the most prevalent forest types – pure spruce and mixed forest stands – were similarly disturbed (62% versus 58% of affected stands, respectively), and species composition in the undisturbed and disturbed stands was very similar, suggesting the disturbance was evenly distributed among forest types. These findings could indicate that tree species composition was probably not a major driver of the disturbance. On the other hand, using the modeling approach, we identified some differences between the two major forest types in their responses to environmental variables. Lack of quantitative data on species composition (as only tree species presence was recorded on historical maps) and low representation of other than dominant forest types in the landscape, however, prevented more detailed analyses of relationships between tree species and disturbance effects.

Given that the disturbance severity was high in pure spruce stands and in mixed spruce, beech and fir stands but low in mixed beech-spruce and pure beech stands, we could expect that there should have been a shift towards beech, but no such sign was

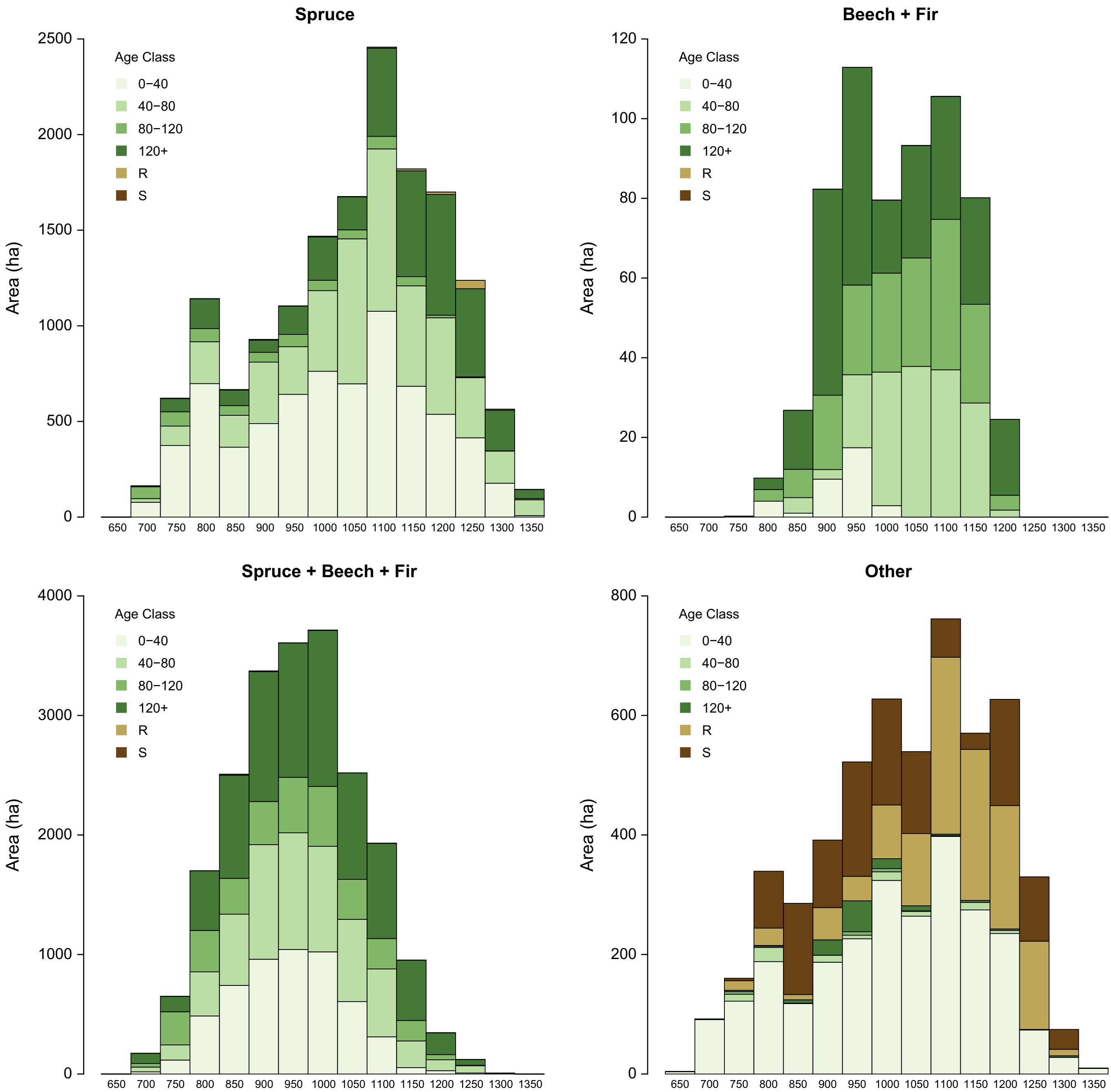

Fig. 7. Age class distribution along elevation gradient (in 50 m intervals) for different species compositions before the 1868–1870 disturbances. Most old-growth (120+) spruce forests were present in elevations higher than 1100 m a.s.l. whereas old-growth spruce, beech and fir mixed forests were more evenly distributed along the elevation gradient.

detected. This could be attributed to the fact that stands which included beech without spruce only accounted for a small proportion of the landscape. The lower amount of completely damaged canopy cover in mixed spruce, beech and fir forests was likely due to mechanical damage to young broad-leaved trees from falling spruce trees (Jelínek, 1988). Subsequent bark beetle outbreaks increased the number of spruce trees killed, while sparing beech and fir, which helps explain the disparity in disturbance severity between the pure spruce and other stand types. Elevation could also underlie this disparity, since pure spruce stands were concentrated mostly at higher elevations (Fig. 4). The greater proportion of young trees in the pure spruce stands than in mixed stands (balanced age classes, slightly dominated by the oldest one), suggests the start of a gradual shift towards pure spruce stands. This would have resulted from previous management and disturbances.

4.3. Modeling the disturbance

The strong effect of age on disturbance severity suggests an important influence of age structure on the scale of such disturbances. Particularly noteworthy, even the unmanaged oldest stands were unable to withstand the extreme winds and subsequent bark beetle outbreak. This finding is important for current management, since many of the stands have already reached the oldest age class. In fact, recent large-scale windthrow events and bark beetle outbreaks might have been direct consequences of

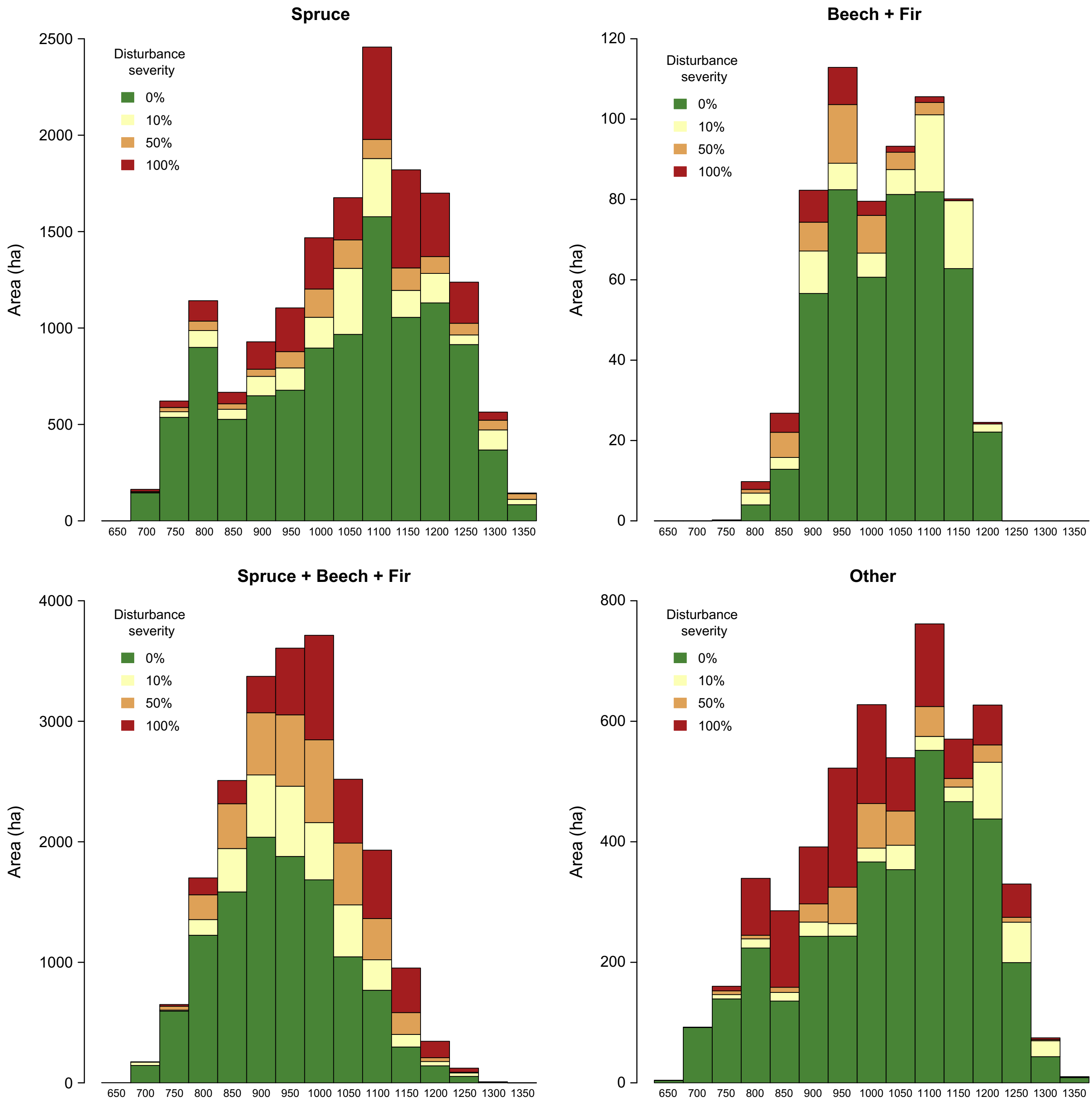

Fig. 8. Disturbance severity along elevation gradient (in 50 m intervals) for different species compositions. Largest areas of spruce forests were disturbed in 1000–1250 m a.s.l. opposing the spruce, beech and fir mixed forests that were mostly disturbed in 850–1100 m a.s.l.

the 1868–1870 disturbance, because at the onset of the recent disturbances (end of 20th century), huge areas were covered with approximately 130-year-old even-aged stands. Similarly, the 1870 disturbance might have been enabled by naturally developed even-aged stands grown after the disturbances of 1710, 1740, or 1778.

Our modeling revealed trends involving elevation effects that invite inquiry into the underlying mechanisms. In particular, although in the model omitting forest stand characteristics (the environmental variable model), both elevation and effective air flow heights were identified as important, they had low predictive power. Additionally, although our analysis of the effect of elevation showed that forests in higher areas were more threatened by disturbances (Fig. 6), as would be expected from higher wind speeds (Malberg, 2007), the highest elevation stands were less disturbed. The finding of decreased disturbance at these elevations could reflect distortion by the presence of only a rather small area of forests in these high elevations, but there could be some other underlying causes. One possibility is that different structure of these stands due to more frequent winds enabled greater tolerance of high winds (Meguro and Miyawaki, 1994). An alternative explanation would be the relatively high proportion of young stands that were remaining in high elevation areas after previous disturbances between the years 1833 and 1840, as documented by Čada et al. (2013) and Svoboda et al. (2012). However, our data did not support this explanation on the landscape scale, as the effects of

Table 3
All explanatory variables used in modeling the disturbance. Those significant in any model are marked bold.

Stand-related, based on historical data:	Topography-related (based on ASTER 2 METI/NASA, 2011):
Mean forest age in 250 m circle, distance to stand with specific age class, age difference of 250 m and 500 m circle, age difference to surrounding stands, presence of spruce, fir, beech and combination, length of stand border, stand area	**Elevation in 250 m circle, slope, aspect, latitude, longitude, country,** morphometric protection index, sky view factor, MAXTOPEX, SAGA wetness index, solar radiation, terrain ruggedness index, relative heights, slope positions, altitude above channel network, **effective air flow heights** from eight principal directions, windward effect, leeward effect, wind effect, sky view factor

elevation and age were significant only for mixed stands. Differences among locations in wind speeds or post-disturbance management practices might explain the highly significant effects of country and latitude.

The lack of significance of topographic variables in the all variable model was unexpected both because some are believed to be important in determining windthrow risk (Mitchell et al., 2008), and even more so because such disturbance risk factors as elevation, MAXTOPEX, and distance to forest edge showed explanatory power in previous modeling of the 2007 Kyrill windthrow in the same area (Mikita et al., 2012). Moreover, distance-limited topex (Quine and White, 1998; Hanewinkel et al., 2004, 2011; Scott and Mitchell, 2005), as well as slope and aspect (Hanewinkel et al., 2004; Mitchell et al., 2008) have been successfully applied in many other areas.

In our study, the lack of significance of these variables was probably due to the large influence of age. Thus, in the environmental variable model, which excluded age-related variables, we identified elevation and effective air flow heights from the east (Boehner and Conrad, 2008) as having some influence on the spatial distribution of disturbance severity, but their predictive power was low. It might also be due to the fact that the position of initial windthrow sites is unknown and was obscured by subsequent bark beetle outbreaks, windthrow events, and management activities. Indeed, for windthrow events of magnitude similar to that examined in our study, 50% of the total disturbance has been attributed to bark beetle damage (Forster et al., 2003). This likely explains why elevation was significant for the mixed stands model, as such stands were less affected by the bark beetle. Moreover, without the salvage logging, the effect of the beetle outbreak might have been greater, but there is no evidence available to examine this possibility, as our data do not let us distinguish among the disturbance components caused by direct windthrow damage, subsequent beetle damage, and salvage logging.

Similarly, the repetitive nature of the windthrow events, in combination with the timing of their recording, may have obscured effects of forest edges, tested via the age difference index. Windthrow events occurred at the beginning of every winter from 1868 through 1870, gradually extending the affected area, with the forest status not recorded between the individual events. Thus, only their cumulative effect is known. Of course, we are also prevented from identifying the influence of bark beetle on the stability of surviving stands due to the summary nature of the data. It should be noted that although we could not distinguish between the damage due directly to wind action, and that of bark beetle infestations and associated salvage logging (and in some ways the effects of these different phenomena might have obscured each other), it is entirely legitimate to consider them in combination, as on the landscape scale they often occur together.

4.4. Use of historical forest management maps

In our study, the historical maps were proven to be useful for assessing the historical range of variability. Their most important benefit is the spatially explicit nature of the data, which allows relating forest species and age structure to disturbance severity as well as environmental and topographic factors. However, their use does have some shortcomings. First, although the data on species presence and stand age are often included in map legends or easily extracted from attached written documents, the data on disturbance or management activities – as was the case in our study – require compilation and interpretation of documents from multiple, different documentary archives, which are available for only very few regions. Second, translation of written documents into maps is time-consuming, subjective work, and its results have to be taken with caution. Additionally, the mapmaking conventions in terms of colors used, age classes, and various markings can differ among countries and even among landowners, complicating the building of seamless maps – especially in cross-border areas such as are common in Central Europe. Furthermore, the information contained in historical documents can be incomplete and therefore restrict its susceptibility to particular analyses. For example, in the maps that we used, only summary disturbance evidence had been recorded during large-scale events, obscuring the individual proportions of stand damage attributable to the wind itself, bark beetle outbreaks, and salvage logging. Despite the challenges and limitations, however, such maps represent a valuable source of data for gaining insight into recent processes and identifying forests' historical range of variability.

5. Conclusions

The use of maps and other archival documents can help reveal an area's historical disturbance regime, its underlying factors, and long-term consequences. Here these sources provided significant insights into the disturbance regime of Central European mountain forests. In particular, we found that forest age was an important factor for disturbance severity, and thus its structure could influence the spatial scale of disturbances. Moreover, we found a large proportion of the forest was old-growth forest, and that it was heavily affected by the large-scale disturbance that occurred within our study period. Thus, the occurrence of both large-scale disturbance and old-growth forest are within the landscape-scale historical range of variability for this region, as also indicated by local stand-scale dendroecological studies from the area. This insight and the identification of factors influencing disturbance susceptibility can help shape management efforts.

A shortcoming of the historical data was that it did not allow us to distinguish the proportions of total disturbance due to windthrow, the ensuing bark beetle outbreak, and salvage logging. However, because the latter two typically follow windthrow events, the damage assessment represents a reasonable appraisal of the actual total impacts of such severe disturbances on the landscape scale.

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