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Slow and fast drivers of the natural disturbance regime in Central European forest ecosystems

Dominik Thom [a], Rupert Seidl [a,*], Gottfried Steyrer [b], Hannes Krehan [b], Herbert Formayer [c]

[a] Institute of Silviculture, Department of Forest- and Soil Sciences, University of Natural Resources and Life Sciences (BOKU) Vienna, Peter Jordan Straße 82, 1190 Vienna, Austria
[b] Department of Forest Protection, Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW), Seckendorff-Gudent-Weg 8, 1131 Vienna, Austria
[c] Institute of Meteorology, Department of Water, Atmosphere and Environment, University of Natural Resources and Life Sciences (BOKU) Vienna, Peter-Jordan Straße 82, 1190 Vienna, Austria

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ABSTRACT

Forest disturbance regimes have intensified in many parts of the world in recent decades, and are an increasing problem for managers concerned with the sustainable and continuous provisioning of forest ecosystem services. In order to address these changes an improved understanding of disturbance regimes is needed, particularly with regard to their main drivers and climate sensitivity. Here, our objectives were to first quantitatively describe the recent disturbance regime of forest ecosystems in Austria (3.99×10^6 ha). Second, our aim was to identify the main drivers of the disturbance regime, distinguishing slow, predisposing factors and fast, inciting factors. We utilized district-level disturbance observations from 2002 to 2010, and focused on damage from wind and bark beetles, the most detrimental abiotic and biotic disturbance agents in Europe. In a two-stage approach, we first analyzed the influence of slow, predisposing variables on the spatial variation in mean disturbance damage, using principle component regression. Subsequently, the year-to-year residuals from these average damage levels were regressed against fast, inciting factors related to disturbance occurrence.

Overall, this two-stage analysis explained 48.7% (wind) and 67.1% (bark beetles) of the spatio-temporal variation in disturbance damage. On average, wind and bark beetles damaged 0.26% and 0.19% of growing stock per year. The analysis of damaged forest areas suggest a mean disturbance rotation period of 746 and 365 years for wind and bark beetle disturbance. Variables related to species composition were the most influential factors on the predisposition to both disturbance agents. Societal factors were found to be of similar importance as climatic variables. Overall, these predisposing (slow) variables had a stronger influence than inciting (fast) drivers, of which weather-related variables and spatio-temporal interactions within the disturbance regime were the most prominent factors.

Our results indicate that important drivers of the disturbance regime can be influenced by forest management directly, but also underline that response times are likely to be slow. Furthermore, fast, inciting factors – although largely beyond the influence of management – have the potential to be used as early warning indicators of impending disturbance damage. Overall, disturbance regimes were found to be highly sensitive to both climate means and extremes, emphasizing the importance for improved risk management in forestry in the face of climate change.

1. Introduction

Natural disturbances are key processes of forest ecosystem dynamics. They shape ecosystem structure at the stand to landscape scale, initiate and reset species succession, and modulate the functioning of forest ecosystems (Franklin et al., 2002; Turner, 2010). Consequently, disturbances have considerable impacts on the provisioning of forest ecosystem services to society. Through a devaluation of wood, the need to harvest prematurely, and negative market effects from large pulses of salvaged timber, disturbances can have a strong disrupting effect on timber production and the timber-based economy (e.g., Nieuwenhuis and O'Connor, 2001; Gardiner et al., 2010). With respect to atmospheric CO_2, disturbance events can turn forests acting as a carbon (C) sink into a C source (Kurz et al., 2008; Seidl et al., 2008; Laurance and Curran, 2008; Hayes et al., 2011; Coomes et al., 2012). They thus have the potential to strongly interfere with objectives to mitigate climate change through forest management (Canadell and Raupach, 2008). Further examples of ecosystem services and functions distinctly affected by disturbances include the protection against

* Corresponding author. Tel.: +43 1 47654 4068; fax: +43 1 47654 4092.
E-mail address: rupert.seidl@boku.ac.at (R. Seidl).

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gravitational natural hazards (Brang et al., 2006) as well as water quality (Emelko et al., 2011). Forest disturbances are thus a key factor in the sustainable management of natural resources.

In recent decades disturbance regimes have intensified drastically in many parts of the globe (e.g., Schelhaas et al., 2003; Westerling et al., 2006). Disturbance damage from wind and bark beetles, the most detrimental abiotic and biotic disturbance agents in Europe's forests, have increased by +2.6% yr^{-1} and +4.2% yr^{-1}, respectively, throughout the second half of the 20th century (Schelhaas et al., 2003). Disturbances are strongly climate sensitive, and the observed increase in frequency and severity has in part been attributed to recent changes in the climate system (Seidl et al., 2011a). For instance, insect reproductive success and survival have strongly increased due to rising temperatures (Battisti et al., 2005). Furthermore, decreasing periods of soil frost have increased the susceptibility of forests to winter windstorms due to weakened anchorage (Usbeck et al., 2010). Future climatic changes are likely to continue this trend towards more disturbances (Seidl et al., 2009; Schelhaas et al., 2010). Considering the potential impacts on ecosystem service provisioning, intensifying disturbance regimes are an increasing concern for forest management (see Lindner et al., 2010).

In order to mitigate potential risks from changing disturbance regimes and enable ecosystem management to respond to these changes, it is of paramount importance to understand the key drivers of disturbance regimes in general, and their climate sensitivity in particular. In this regard recent years have brought about a considerable increase in our quantitative understanding of disturbance processes (Johnson and Miyanishi, 2006; Seidl et al., 2011b). In depth analyses of recent disturbance events, for instance, have led to the identification of major drivers of disturbance susceptibility (e.g., Valinger and Fridman, 2011; Overbeck and Schmidt, 2012). Looking beyond individual events, fewer studies to date have addressed the disturbance regime, and the intra- and inter-agent interactions over space and time. Valuable information in this regard, for example concerning disturbance return intervals or the spatio-temporal interactions between disturbance agents, comes from tree ring-based disturbance reconstructions for old-growth forest ecosystems (Nagel et al., 2007; Svoboda et al., 2012). These studies provide information on the historical range of variability of forest ecosystems (Keane et al., 2009). However, their applicability to forest ecosystems altered by centuries of anthropogenic use – as prevalent in Central Europe – is often limited, because the resulting changes in forest structure and composition profoundly affect disturbance processes (Seidl et al., 2011a). Characterizing natural disturbance regimes in human-dominated landscapes thus requires the consideration of both ecological and societal drivers, i.e., a coupled human and natural systems perspective (Liu et al., 2007).

Focusing on wind and bark beetles, the two most important disturbance agents in Europe's forests, our objective here was to characterize the recent disturbance regime in Central European forest ecosystems. Our specific aims were twofold: First, to derive descriptive disturbance metrics for the forests of Austria (3.99×10^6 ha). In the context of intensifying disturbances our goal was to provide a quantitative characterization of the disturbance regime of the recent past (2002–2010) as a baseline for the assessment of modeled and observed changes in the future. Second, our aim was to identify the main drivers of the disturbance regime in the human-dominated landscapes of Central Europe. Since an important means to understanding complex systems is the explicit consideration of fast and slow variables (Carpenter and Turner, 2001; Walker et al., 2012), we explicitly distinguished slow, predisposing factors from fast, inciting factors as drivers of the disturbance regime (see also the theory of tree death proposed by Manion (1981)), and considered both ecological and societal indicators in our analyses. A particular focus was to identify indicators that can potentially be influenced by forest management in order to counteract intensifying disturbance regimes, and variables that have the potential to serve as early warning indicators of disturbance damage in the context of risk management.

2. Materials and methods

2.1. Disturbance data

Data on wind and bark beetle disturbance (see Table S1 in the online supplement for the species considered) for the years 2002–2010 were recorded by district foresters under the guidelines of the Austrian Documentation of Forest Damage Factors (Steyrer et al., 2011), a program ran by the Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW). Data on disturbance area (ha) and impact (m^3 stemwood damaged) were compiled and quality-checked at BFW. The temporal resolution of the disturbance record is annual and its spatial grain is the forest district level ($n = 72$), covering the forest area of Austria (3.99×10^6 ha). Forest districts are administrative landscapes of between 17,690 and 278,900 ha in size (mean 116,600 ha), with a forest area of between 3,000 and 113,000 ha per district (mean 46,510 ha). Districts are more than two orders of magnitude larger than the average area disturbed by wind and bark beetles in the observation period, and are thus of sufficient size to be considered quasi-equilibrium landscapes in the context of disturbance analysis (see Urban, 1987).

2.2. Potential drivers of the disturbance regime

To identify major drivers of the spatio-temporal variation in Austria's disturbance regime we compiled a wide range of potential explanatory variables at the level of forest districts. Our *a priori* assumptions on their relationship to disturbance damage were based largely on previous insights on disturbance processes (e.g., Wermelinger, 2004; Gardiner et al., 2010; Usbeck et al., 2010; Seidl et al., 2011a). Factors potentially influencing disturbance susceptibility and characterized by a slow rate of change over time (i.e., changing on decadal to century scale and beyond) were summarized as slow variables in our analysis, and include aspects of vegetation structure and composition, climate, as well as forest stewardship (see Table 1 for variable definition and data sources). These factors were assumed to be constant over the study period, and spatial averages for the district forest area were used in the analysis.

Factors changing on annual and intra-annual time scales were summarized as fast drivers, and relate to inciting factors *sensu* Manion (1981). These include weather variables as well as variables describing spatial and temporal disturbance interactions (see Table 2 for details). Weather variables were included as monthly anomalies to the long-term (1971–2000) mean (ZAMG, 2012b,c), and were interpolated to district centroids from weather station data by means of ordinary kriging (Bivand et al., 2008). We used individual variogram models for every month of the analysis, thus accounting for the different synoptic situation of every month in the interpolation (spatial patterns often differ between summer- and winter months in mountain areas, e.g., as a result of inversion). While this approach of spatially representative anomalies was deemed suitable for temperature- and precipitation-related variables, the high local variability in wind speed as well as the limited information of weather station data with regard to peak winds (i.e., the variable of interest in the context of wind disturbance) prevented the use of the same data source to also characterize the wind climate. However, a recent synthesis by Gardiner et al.