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Using Landsat time series for characterizing forest disturbance dynamics in the coupled human and natural systems of Central Europe

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A B S T R A C T

Remote sensing is a key information source for improving the spatiotemporal understanding of forest ecosystem dynamics. Yet, the mapping and attribution of forest change remains challenging, particularly in areas where a number of interacting disturbance agents simultaneously affect forest development. The forest ecosystems of Central Europe are coupled human and natural systems, with natural and human disturbances affecting forests both individually and in combination. To better understand the complex forest disturbance dynamics in such systems, we utilize 32-year Landsat time series to map forest disturbances in five sites across Austria, the Czech Republic, Germany, Poland, and Slovakia. All sites consisted of a National Park and the surrounding forests, reflecting three management zones of different levels of human influence (managed, protected, strictly protected). This allowed for a comparison of spectral, temporal, and spatial disturbance patterns across a gradient from natural to coupled human and natural disturbances. Disturbance maps achieved overall accuracies ranging from 81% to 93%. Disturbance patches were generally small, with 95% of the disturbances being smaller than 10 ha. Disturbance rates ranged from 0.29% yr^{-1} to 0.95% yr^{-1}, and differed substantially among management zones and study sites. Natural disturbances in strictly protected areas were longer in duration (median of 8 years) and slightly less variable in magnitude compared to human-dominated disturbances in managed forests (median duration of 1 year). However, temporal dynamics between natural and human-dominated disturbances showed strong synchrony, suggesting that disturbance peaks are driven by natural events affecting managed and unmanaged areas simultaneously. Our study demonstrates the potential of remote sensing for mapping forest disturbances in coupled human and natural systems, such as the forests of Central Europe. Yet, we also highlight the complexity of such systems in terms of agent attribution, as many natural disturbances are modified by management responding to them outside protected areas.
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1. Introduction

Forest disturbances shape the structure and composition of forests for many decades, and thus play a vital role in ecosystem functioning and service provisioning (Turner, 2010). Disturbance rates in temperate forests have increased in recent decades (Cohen et al., 2016; Seidl et al., 2014), and there is evidence that climate change and past land use both have contributed significantly to this observed increase in disturbance activity (Franklin et al., 2002; Seidl et al., 2011). Yet, our understanding of the causes and consequences of disturbances remains incomplete, in part because of a limited inferential potential of established methods in forest ecology (e.g., repeated plot-based forest inventory, dendroecology) regarding the spatiotemporal patterns created by disturbances. A prerequisite for a better understanding of disturbance regimes is the accurate reconstruction of past forest disturbance dynamics at spatial, temporal, and thematic scales that will allow advanced ecological analyses (McDowell et al., 2015). In this regard, it has long been suggested that the spatially and temporally explicit view offered by time series from the Landsat sensor family can help tackle the challenge of a comprehensive disturbance inventory (Cohen and Goward, 2004).

The opening of the Landsat archive in 2008 has substantially changed the way Landsat is used for mapping forest ecosystem

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change (Wulder et al., 2012). The dense time series information now available allows for a seamless mapping of forest disturbances at annual intervals (Hansen et al., 2013), and for the characterization of disturbances in terms of disturbance magnitude and duration (Kennedy et al., 2014). These new information streams enable the quantification and attribution of recent disturbance activities within a region (Kennedy et al., 2012a). Yet, studies on disturbance mapping and characterization have to date either largely focused on ecosystems characterized by large-scale natural disturbances (e.g., forest fires and insect outbreaks), or on areas characterized by relatively simple (in terms of spatiotemporal patterns) human disturbances, e.g. in the western US or Canada (Hermosilla et al., 2015b; Kennedy et al., 2012a; Meigs et al., 2015; White et al., 2017). However, many forest ecosystems around the globe are driven by natural disturbances that are relatively small in scale and/or have low severity (e.g., blowdown of patches of trees, mortality from pathogens). Furthermore, management regimes are often temporally and spatially complex, e.g. in areas characterized by small-scale ownership structure. Moreover, natural disturbances and human disturbances are often not independent events, particularly in densely populated and actively managed landscapes, where forest management frequently aims to contain the spread of disturbance or salvage disturbed timber (Lindenmayer et al., 2012; Stadelmann et al., 2013). Hence, disturbances in such coupled human and natural systems are more complex than in systems dominated by natural disturbances, yet little knowledge about their spectral, temporal, and spatial patterns exists.

The forests of Central Europe are prime examples of coupled human and natural system. Most of the forested area in the region is under intensive human use (Levers et al., 2014), and has been influenced by humans and intensively managed for centuries (Bebi et al., 2017; Munteanu et al., 2015). In recent decades, there has been great effort to protect parts of the European forests in order to conserve forest biological diversity, yet less than 1% of the total forest area in Central Europe is allowed to develop freely without any management (Parviainen and Frank, 2003), and only 0.4% of the forests in Europe are considered old-growth (Parviainen, 2005). Despite the intensive management, forests in Central Europe are also prone to natural disturbances, with wind and bark beetles being the most important disturbance agents (Schelhaas et al., 2003; Seidl et al., 2014). Both agents strongly interact with each other (Seidl and Rammer, 2016; Stadelmann et al., 2014), and respond to changes in the climate system and human land use (Kulakowski et al., 2017; Seidl et al., 2011). However, natural disturbances are actively managed in the vast majority of forests in Central Europe, restricting the study of natural disturbance regimes to areas where human intervention is excluded (i.e., protected forests). Outside protected forests, sanitary felling and salvage logging are routinely applied to recover economic losses from disturbances, and to prevent the spread of bark beetle outbreaks (Stadelmann et al., 2013). Hence, forests in Central Europe are affected by natural and human disturbances both individually and in combination, making the distinction between natural and human disturbances challenging and not always meaningful. Since natural forest disturbance dynamics are, however, an important guiding indicator for ecosystem management (Cyr et al., 2009; Kulakowski et al., 2017), a better understanding of natural disturbances dynamics in Central Europe, as well as the effect of management on natural disturbances, is urgently needed.

In order to improve our understanding of natural disturbance dynamics and the effect of management upon those, we here make use of Landsat time series analysis to contrast forest disturbance dynamics and characteristics within protected forests (natural disturbances) to forest disturbance dynamics and characteristics in their surrounding managed forests (human-dominated disturbances). That way, we aim at gaining a better understanding of the gradient from natural to coupled human and natural disturbances present in Central European forests. Specifically, our objectives were to:

(1) Map forest disturbances across five protected forests and their surrounding managed forests in Austria, the Czech Republic, Germany, Slovakia, and Poland, using 32 years of Landsat observations (1985–2016).
(2) Characterize and compare forest disturbances among protected and managed forests to understand the effect of management on spectral, temporal, and spatial characteristics of forest disturbances in coupled human and natural systems.

2. Study sites

We here focus on five forest sites in Austria, the Czech Republic, Germany, Slovakia, and Poland (Table 1; Fig. 1). The sites represent a wide variety of the forest types and ecological conditions occurring in Central Europe. All five sites are national parks with a strictly protected core zone. While the strictly protected core zones of each national park prohibit all human interventions, the management zones contained in each national park can be under active management, yet park authorities usually aim at limiting management to a minimum. In Central Europe, this usually means sanitation felling and salvage logging to prevent the percolation of bark beetle outbreaks into areas adjacent to the national park. In addition to the five national parks, a 30 km buffer around the national park boundaries was included in the analysis of the five sites (Fig. 1). These buffers are characterized by managed forests of varying management intensity.

According to the European Environmental Agency (EEA) European forest type classification (European Environmental Agency, 2006), lower-elevation forests across all sites are characterized by beech-dominated forest types (*Fagus sylvatica* L.), transitioning into mixed mountain forest types at elevations of about 800 m a.s.l (dominated by *F. sylvatica*, Norway spruce *Picea abies* (L.) Karst., and silver fir *Abies alba* Mill.). In higher elevation regions (roughly >1200 m a.s.l.), forests are characterized by coniferous forests dominated by Norway spruce, with the importance of European larch (*Larix decidua* Mill.) increasing with elevation. The tree line (approximately at 1800 m a.s.l., but varying throughout the region) is characterized by a krummholz belt of mountain pine (*Pinus mugo* Turra).

3. Data and methods

3.1. Landsat processing

We downloaded all available Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) images from the United Stated Geological Service (USGS) and European Space Agency (ESA) archives. All L1T images were corrected to surface reflectance using the LEDAPS algorithm (Masek et al., 2006), except for Landsat OLI, for which we used the methods described in Vermote et al. (2016). Images from ESA were geometrically corrected using the AROP algorithm (Gao et al., 2009) to improve spatial alignment with images from the USGS archive. We used Fmask for creating cloud and cloud-shadow masks (Zhu and Woodcock, 2012). Further, we excluded coastal, cirrus, thermal and panchromatic bands and transformed the six remaining Landsat spectral bands into Tasseled Cap (TC) space to derive brightness, greenness, and wetness components (Crist, 1985). The TC components have routinely been used for

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