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

Authors: Cornelius Senf[1,2], Dirk Pflugmacher[1], Patrick Hostert[1,3], and Rupert Seidl[2]

Affiliations: [1]Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany; [2]Institute for Silviculture, University of Natural Resources and Life Sciences (BOKU) Vienna, Peter-Jordan-Str. 82, 1190 Vienna, Austria; [3]Integrative Research Institute on Transformation of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

Corresponding author: cornelius.senf@geo.hu-berlin.de

Submitted to: *ISPRS Journal of Photogrammetry and Remote Sensing*

Submitted on: 12th May 2017

Submitted in revised form: 27th June 2017

Accepted: 8th July 2017

DOI: https://doi.org/10.1016/j.isprsjprs.2017.07.004

Abstract: 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.

Keywords: Disturbance mapping; Landsat; Harvest; Bark beetle; Wind; Forest management

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 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 disturbances 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 30km 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.

Table 1: Summary of the five study landscapes. All landscapes consist of the respective national parks and a 30km buffer zone of managed forests surrounding them. Bark beetle here refers mainly to the European spruce bark beetle (*Ips typographus* L.).

Site	Year of establishment	Total size (km^2; managed/protected/strictly protected)	Countries	Main disturbance evens since 1985
Berchtesgaden	1978	1194 (986/179/29)	Austria/Germany	Storms Vivian/Wiebke (1990) as well as Kyrill (2007) and Emma (2008), followed by increased bark beetle activity
Bohemian Forest	1970 (Bavarian Forest)/1991 (Šumava)	3114 (2183/836/95)	Austria/Czech Republic/Germany	Two waves of bark beetle outbreaks in the late 2000s and 2010s, local impacts of storm Kyrill (2007).
Harz	1990 (East-Germany)/1994 (West-Germany)	1496 (1248/119/129)	Germany	Storm Kyrill (2007) and following bark beetle outbreaks
Kalkalpen	1997	1339 (1131/52/156)	Austria	Storms Vivian/ Wiebke (1990) as well as Kyrill (2007), Emma (2008), and Paula (2008), followed by increased bark beetle activity
Tatra	1949 (Slovakia)/1954 (Poland)	2756 (1676/1015/65)	Poland/Slovakia	Storm events in 1988 and 1989, particularly severe Bora-type storm event in 2004, followed by high bark beetle activity

According to the European Environmental Agency 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 >1,200 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 1,800 m a.s.l., but varying throughout the region) is characterized by a krummholz belt of mountain pine (*Pinus mugo* Turra).

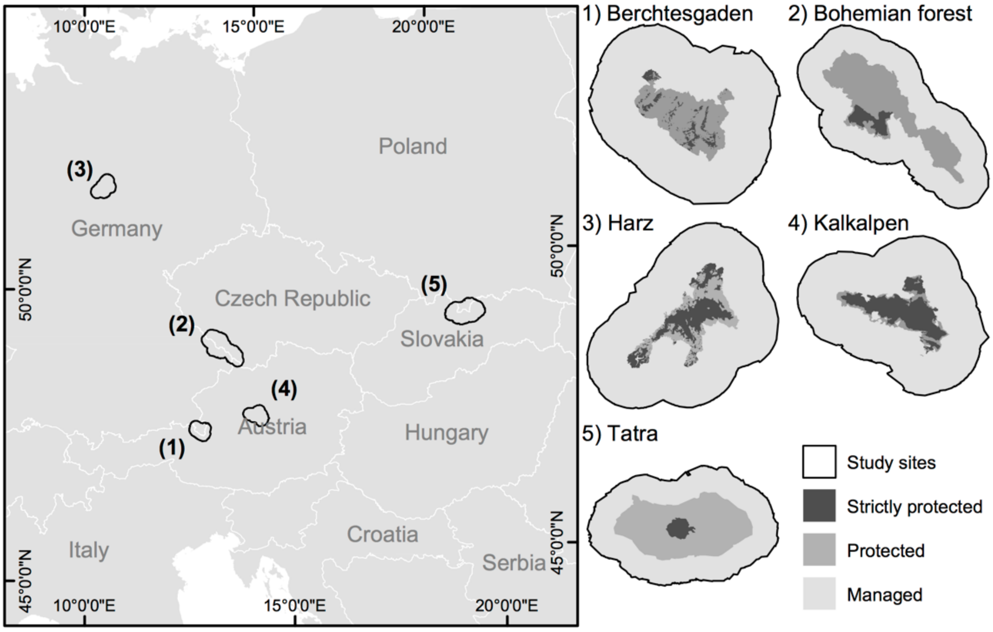

Figure 1: Location and protection status of the five study sites.

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 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 detecting forest disturbance in North America (e.g., Healey et al. 2005; Senf et al. 2015; Wulder et al. 2006), and also proved useful in a previous case study in Europe (Hais et al. 2009). For all three TC components, we developed annual summer median composites using all available cloud-free observations (Rufin et al. 2015). We selected cloud-free observations between June 1st and August 31st to capture summer maximum vegetation conditions (Senf et al. 2017), except for the Tatra site, where we extended the time frame to October 31st, in order to counterbalance lower data availability.

3.2 Disturbance mapping

3.2.1 Reference data collection

We applied a stratified random sampling design to select 500 Landsat pixel center locations per study site, with sampling strata based on a disturbance magnitude estimate (see Section 3.2.2 for further information). Samples were classified into five classes using Jenk's natural breaks classification (Pflugmacher et al. 2012). The sampling unit was defined as one Landsat pixel (30 × 30 meters), and we focused on stand-replacing disturbances at this spatial grain. For each sampling unit, a trained interpreter estimated the land cover and disturbance history following the procedures described in Cohen et al. (2010), previously applied in a wide range of forest disturbance studies in other study areas (Cohen et al. 2016; Griffiths et al. 2014; Hermosilla et al. 2015b; Kennedy et al. 2012a; Potapov et al. 2015; Thomas et al. 2011). In particular, we first determined the land cover in 1985 to create a forest mask by visually interpreting the 1985 TC composite and, where available, high resolution imagery. Second, we assessed whether a disturbance occurred between 1985 and 2016 for each sampling location. A disturbance was defined as an abrupt or gradual change visible in the TC time series, resulting from either removal or natural mortality of the majority of trees within a pixel. Since it is difficult to assess percent canopy change from Landsat time series, we applied a minimum spectral change threshold and labeled all spectral changes larger than this threshold as disturbance. In particular, a sampling unit was assessed as being disturbed if the relative change in TC brightness was greater than 40%, assuming that a substantial proportion of soil reflectance is required to qualify a disturbance as stand-replacing (i.e. residual canopy cover being <50%). We evaluated the chosen spectral change threshold using Lidar data available for two sites (Bohemian Forest and Kalkalpen), comparing the canopy cover for trees >5m for disturbed and undisturbed reference pixels. This analysis confirmed that 96.30% of the disturbed reference pixels had a residual canopy cover <50%. We furthermore corroborated our disturbance classification using high-resolution imagery where available. Third, we estimated the year of disturbance based on the first year of spectral change observable in the TC wetness trajectory. Finally, we randomly split the 500 reference pixels per site into one subset for calibration and one for validation (Table A1 in the Appendix).

3.2.2 Mapping workflow

We applied a hierarchical classification workflow (Fig. 2) to map disturbances for each site individually: First, we created a forest mask for the beginning of the study period in 1985. We then created a binary map of undisturbed and disturbed forest pixels between 1985 and 2016. Both maps were subsequently combined into one map containing three classes: No forest, undisturbed forest, and disturbed forest. This map was then validated using the reference data held back during model calibration. Finally, the disturbance year was determined for each disturbed pixel.

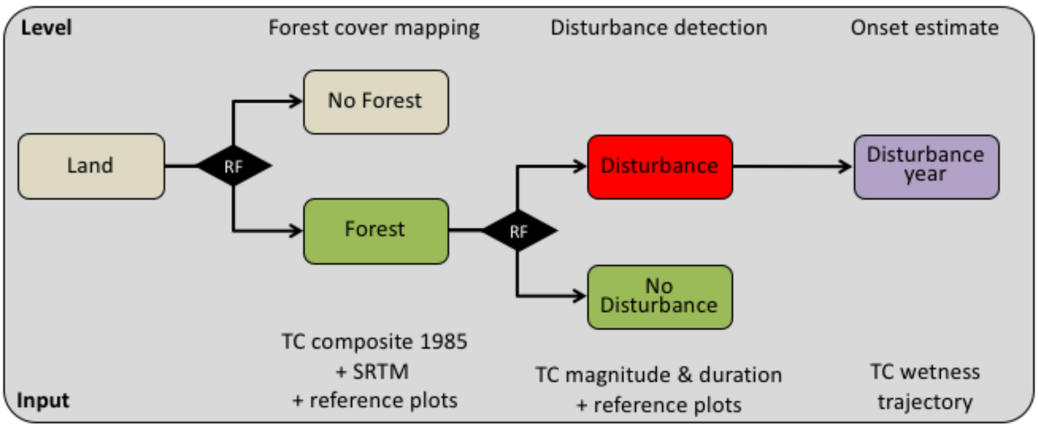

Figure 2: Visualization of the hierarchical disturbance mapping workflow employed in this study.

For creating the forest mask, we trained a random forest model (Breiman 2001) based on the initial year's TC composites. We further used a digital elevation model as input to the classification (*Shuttle Radar Topographic Mission* [SRTM] data with 90 m spatial resolution, which was resampled to 30 m using bilinear interpolation); as well as slope values calculated from the digital elevation model. We used the land cover information available in the calibration data for training (see Section 3.2.1).

For detecting disturbances, we made use of a recently developed disturbance detection algorithm (*shapeselectionforest;* Moisen et al. (2016)). The algorithm fits six pre-defined splines to each pixel's spectral trajectory and identifies the best fitting spline using Bayes Information Criteria (BIC). We applied *shapeselectionforest* to all three TC composite time series individually, assuming that TC wetness would decrease when forests are disturbed, whereas TC brightness and greenness would increase (Hais et al. 2009). We filled each missing observation with the mean of the four neighboring observations before fitting the splines to account for missing pixels in the spectral time series (e.g. from remnant clouds, shadows, missing observations from Landsat 7's failed scan line corrector). We excluded the pixel from further analysis if more than five missing values occurred in a time series, as we noted substantial misfits with more than five missing observations during initial data exploration.

From the best fitting spline, we extracted two disturbance metrics for each TC component: disturbance magnitude and disturbance duration (for further information on the disturbance metrics see Moisen et al. 2016). We used those disturbance metrics as input to a second random forests model, which was trained using the disturbance occurrence information available in the calibration data (see Section 3.2.1). We created a final map with the categories non-forest, undisturbed forest, and disturbed forests for each study site by applying the second random forest model to all areas identified as forested in the previous classification. We subsequently applied a minimum mapping unit of 0.5 ha to create the final map, i.e. only disturbances affecting six or more Landsat pixels were mapped.

We determined the disturbance year for all disturbed pixels using the spline fitted to the TC wetness time series, because a decrease in TC wetness correlates best with changes in the upper tree canopy, whereas changes in TC brightness and greenness are more influenced by understory and regeneration responses than TC wetness (Hais et al. 2009). Further, we adjusted the time estimate from the spline model to match the time estimate from the interpreter. Specifically, splines characterizing disturbances that occurred over several years systematically estimated earlier disturbance onsets than the interpreter. To be consistent with the reference data, we matched the spline estimate by calculating the mean difference between the spline estimate and the disturbance onset recorded in the calibration data. The mean difference was subsequently applied to match the estimated disturbance onset for all pixels. Finally, we dropped all disturbances occurring in 1985, as disturbance detection in the starting year is generally unreliable (Cohen et al. 2017).

For each study site, we evaluated the overall accuracy and class-specific commission and omission errors following the approach suggested by Olofsson et al. (2014). In particular, we weighted each observation according to its inclusion probability stemming from the stratified sampling design employed in this study. The approach then uses a post-stratified estimator to estimate overall accuracy and class-specific errors of the final disturbance maps. The error of the disturbance onset was evaluated by calculating the root mean squared error (RMSE) between the disturbance onset estimated from Landsat data and the onset recorded in the validation data, as well as the percentage of correctly classified onset dates.

3.3 Analysis of disturbance dynamics and characteristics

We used the spatial information on the protection status (Fig. 1) to stratify each site into three management zones: 1) managed, 2) protected, 3) strictly protected. This allowed for assessing the effect of management on spatiotemporal disturbance dynamics, as well as on the spectral-temporal characteristics of forest disturbances. Disturbance patterns within strictly protected forests are solely driven by natural disturbance agents. Disturbances in protected forests (i.e., the management zones of national parks) result from the combined effect of natural disturbances and management. Natural disturbances in the protected zones of national parks are often salvaged in Central Europe, meaning that disturbed trees are removed from site to prevent the spread of bark beetles breeding in those trees. Furthermore, also sanitation logging, that is removing live but susceptible trees, or trees that are in the green attack stage, is also applied within the management zones of national parks, in order to prevent the spread of bark beetle outbreaks across the park boundary (Wermelinger 2004). Disturbances in the forests outside of national park boundaries mostly result from harvesting activities. Harvests can be planned, but might also be triggered by natural disturbances. In particular, sanitation felling of bark beetle infested trees in the green attack stage or susceptible trees in the vicinity of previous attacks is a common management practice in Central Europe (Stadelmann et al. 2013). Furthermore, salvage logging of wind-felled trees is common to prevent the build-up of bark beetle populations (Stadelmann et al. 2013; Thorn et al. 2014). For all sites and management zones, we calculated average annual disturbance rates based on the forest cover estimated for 1985, and annual changes in disturbance areas. Further, we derived disturbance patch size distributions by site and management zone. We identified connected disturbance patches using an eight-neighbor moving window approach. Finally, we compared the spectral-temporal disturbance characteristics derived from the Landsat time series analysis (see Section 3.2.2) among the three management zones.

4. Results

4.1 Disturbance mapping accuracies

The disturbance mapping resulted in overall accuracies ranging from 82% to 93% (Table 2). Disturbance commission and omission errors were highly variable across sites, with highest disturbance commission estimated for the Berchtesgaden site (24%), and highest disturbance omission estimated for the Harz site (28%). For the undisturbed class, commission errors ranged between 3% (Bohemian Forest) and 20% (Kalkalpen), and omission errors between 8% (Kalkalpen) and 20% (Bohemian Forest). Non-forest area was mapped with commission errors ranging from 5% (Tatra) to 25% (Bohemian Forest) and omission errors ranging from 0.5% (Harz) to 35% (Kalkalpen). The year of disturbance (Fig. 3) was estimated with errors ranging from 3.1 to 4.3 years (Table 2). In total, >60% of the reference pixels were assigned the correct year (except for the Bohemian Forest site), which increased to >80% if the matching threshold was set to ±1 year (except for the Tatra site; Table 2).

Table 2: Overall accuracy, omission and commission errors, as well as errors in the disturbance year for the five landscapes.

Site	Overall accuracy [%]	Class-specific errors [%]						Year of occurrence		
		Disturbed		Undisturbed		Non-forest		RMSE [years]	Percent correct	
		Commission	Omission	Commission	Omission	Commission	Omission		±0 years	±1 years
Berchtesgaden	81.45	23.75	11.43	17.13	17.51	19.45	20.76	3.96	75.00	86.54
Bohemian Forest	87.31	5.12	2.80	3.29	19.94	25.24	3.70	4.26	55.17	80.46
Harz	88.51	17.15	27.53	4.21	17.63	16.66	0.54	3.14	64.86	82.43
Kalkalpen	82.29	16.44	9.71	20.23	7.99	12.26	35.38	3.26	74.42	90.70
Tatra	92.62	6.64	15.25	12.06	8.55	5.41	4.84	3.78	67.24	70.69

Table 3: Disturbance rates.

Site	Disturbance rates (% of forest area disturbed per year)			
	Total	Strictly protected	Protected	Managed
Berchtesgaden	0.29	0.22	0.30	0.29
Bohemian Forest	0.58	1.73	0.78	0.39
Harz	0.48	0.68	0.66	0.46
Kalkalpen	0.47	0.23	0.54	0.53
Tatra	0.95	0.56	1.18	0.76

4.2 Spatiotemporal dynamics of forest disturbances

From the disturbance maps (Fig. 3) we estimated mean annual disturbance rates ranging from 0.3% (Berchtesgaden) to 1% (Tatra). Disturbance rates varied substantially among the three management zones (Table 3). For the Berchtesgaden, Kalkalpen and Tatra sites disturbance rates were lowest in strictly protected areas. Conversely, in the Bohemian Forest and Harz sites, lowest disturbance rates were found in managed forests. Highest disturbances rates were generally found in protected forests, except for the Bohemian Forests, where the highest disturbance rate was found in strictly protected forests.

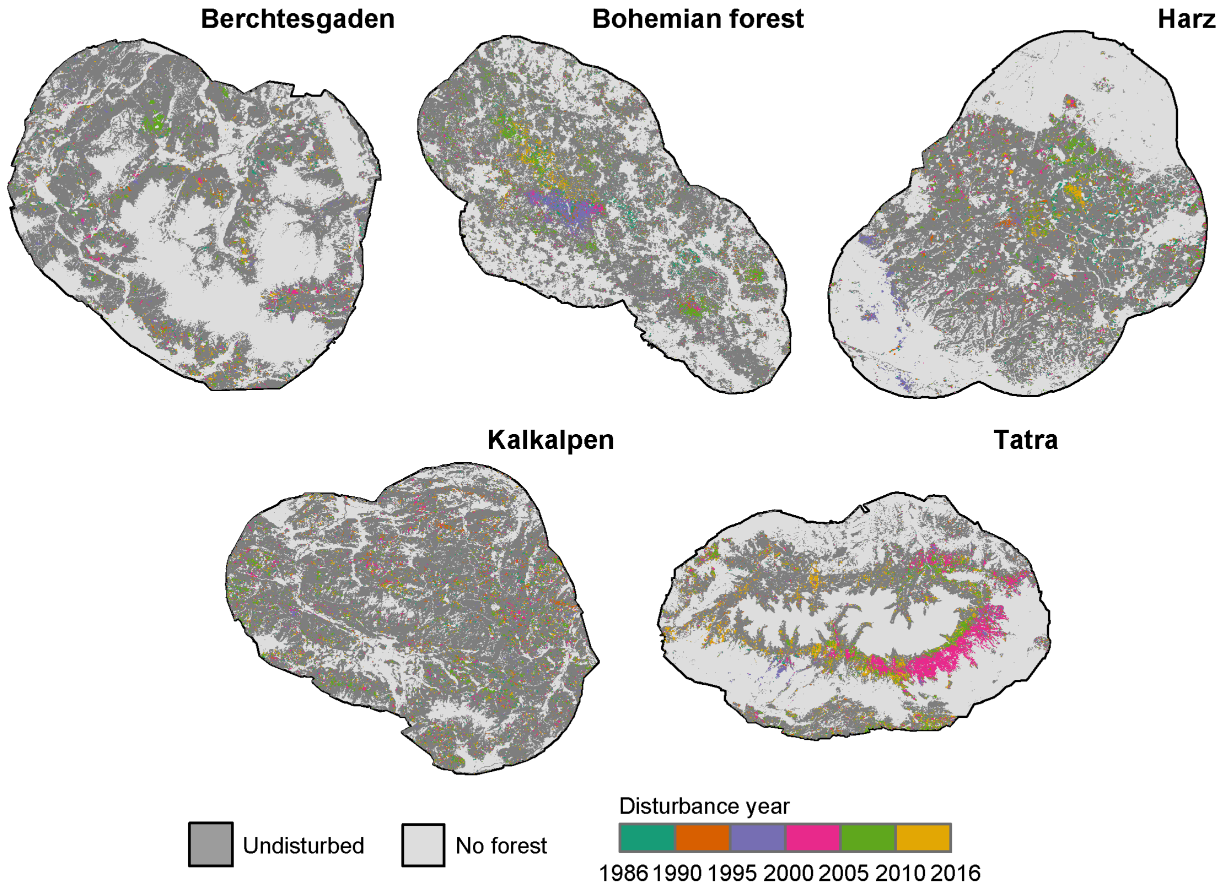

Figure 3: Spatiotemporal disturbance dynamics mapped from Landsat. Annual disturbance years are grouped in 5-year steps to facilitate visualisation.

The disturbance patch size distributions were highly right-skewed for all sites (Table 4), with – averaged over all sites and management zones – 45 % of the disturbance patches being smaller than 1 ha, and 95% of the disturbances patches being smaller than 10 ha. We did not find substantial differences in median patch size among sites and management zones. Yet, maximum patch sizes varied considerably among sites and management zones (Table 4). Largest patches were either found in protected forests (Bohemian Forest [6,679 ha] and Tatra [12,801 ha]), in strictly protected forests (Harz [329 ha]), or in managed forests (Berchtesgaden [211 ha] and Kalkalpen [170 ha]).

Table 4: Patch size summary.

Site	Patch size [ha]								
	Strictly protected			Protected			Managed		
	Median	95% quantile	Maximum	Median	95% quantile	Maximum	Median	95% quantile	Maximum
Berchtesgaden	1.17	5.56	13.5	1.08	13.64	51.12	1.17	8.46	211.86
Bohemian Forest	1.17	15.22	269.46	1.17	10.80	6,679.26	1.08	7.74	549.36
Harz	1.35	25.61	329.13	1.26	18.45	145.89	1.26	14.76	124.65
Kalkalpen	0.99	7.13	77.67	1.22	10.98	56.43	1.26	9.72	169.56
Tatra	1.08	9.79	183.15	1.17	18.36	12,801.33	1.26	17.16	1,046.25

The temporal analysis of disturbance dynamics (Fig. 4) revealed a general synchrony in the variation of disturbed area among the three management zones within each site. A strong peak in disturbed area was observed around the years 2007. Only at the Tatra site disturbances peak in 2005. Both dates correspond to large storm events that have affected our study sites across all three management zones (Table 1).

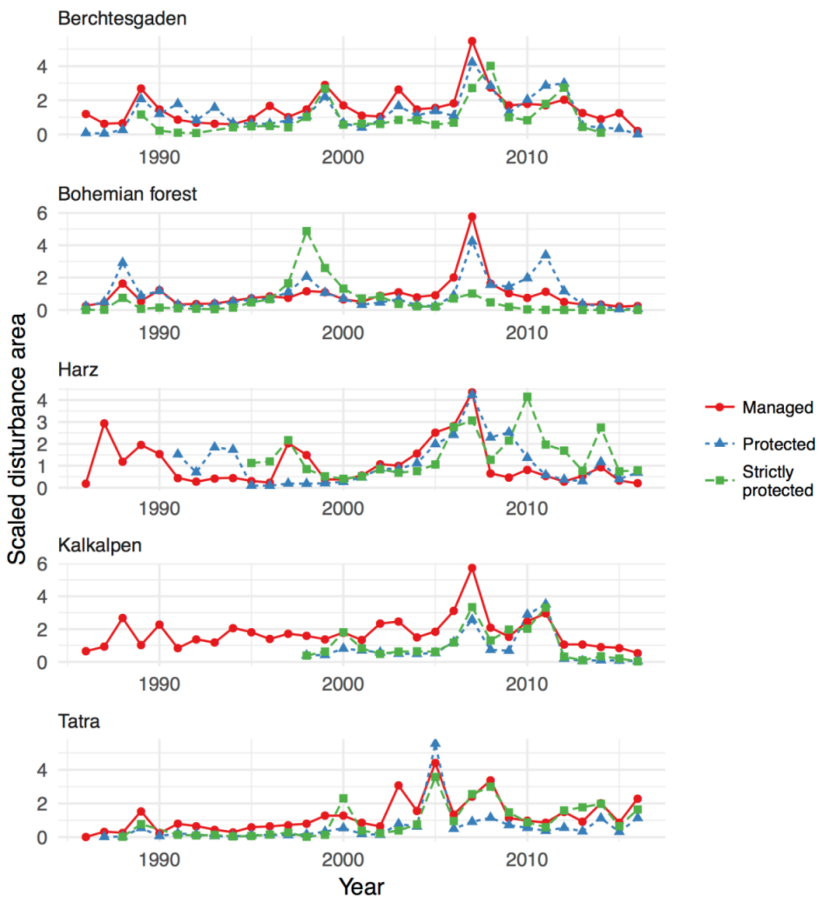

Figure 4: Temporal disturbance dynamics. Note that for facilitating comparisons among management zones, disturbances areas were scaled to units of standard deviation.

4.3 Spectral-temporal disturbances characteristics

We found distinct differences in disturbance duration among strictly protected, protected, and managed forests (Fig. 5). Most notable was a longer disturbance duration in strictly protected forests, which was most obvious in the TC wetness component. Disturbances in strictly protected forests had a median disturbance duration of eight years for TC wetness, with only 19% of the disturbances being shorter than three years. Disturbances in managed and protected forests had a median duration of only one year, with 58% (managed) and 51% (protected) of the disturbances being shorter than three years. Hence, disturbances in managed and protected forests were dominated by short-duration disturbances, whereas disturbances in strictly protected forests had a considerably longer duration.

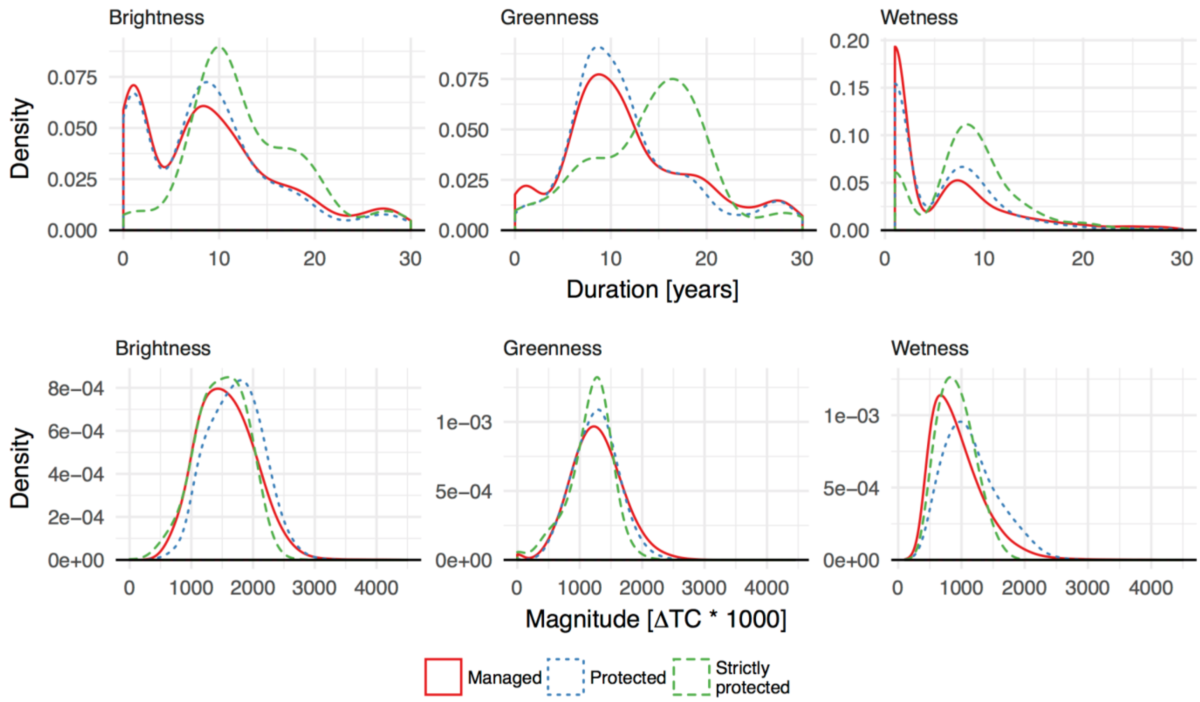

Figure 5: Spectral-temporal properties of disturbances in strictly protected, protected, and managed forests. Plots show empirical probability density functions as estimated using a Gaussian kernel density estimator.

Spectral magnitude showed a less clear picture, with no substantial differences in median spectral magnitudes across management zones (Fig. 5). Slightly higher variability in spectral magnitudes was found in management and protected forests, and very high-spectral magnitude disturbances (change in wetness > 2,000 and changes in brightness > 2,500) were rarely found in strictly protected forests.

5. Discussion

5.1 Mapping forest disturbances in coupled human and natural systems

Studies using earth observation data for mapping forest disturbances in complex coupled human and natural systems are rare, and we thus lack a deeper understanding of the potential and challenges of Landsat-based algorithms for mapping and characterizing forest disturbances in these systems. Our study contributes towards filling this gap by mapping forest disturbance from Landsat time series across five sites representative of the forests of Central Europe. Overall, we achieved classification accuracies being comparable to, or slightly lower than, those achieved by studies in North America (Hermosilla et al. 2015b; Kennedy et al. 2012a). Given the higher complexity in spatial disturbance patterns in Central Europe – i.e., a much smaller patch size compared to North America and a thus higher abundance of mixed pixels – our results encourage the use of Landsat time series for a wider reconstruction of disturbance dynamics in Europe.

Besides good classification results overall, however, we found substantial variation in classification accuracies among study sites. This variation in classification accuracies suggests that site-specific factors can influence the large-scale mapping of forest disturbances. Our five study sites span a gradient from mid-elevation landscapes with relatively mild topography (i.e., Bohemian Forest and Harz) to high elevation and alpine landscapes characterized by rough and steep terrain (i.e., Kalkalpen, Berchtesgaden). High commission errors of undisturbed forests and high omission errors of non-forest areas were particularly found for the sites situated in the northern front range of the Alps (Kalkalpen and Berchtesgaden). At those sites, high elevation forests are often characterized by open canopies and a clustered arrangement of trees, resulting from a decreasing number of microsites suitable for tree growth due to rock outcrops and a transition into *krummholz* formations of mountain pine. Those *krummholz* formations are spectrally similar to lower elevation pine and spruce forests, though not defined as forests here, since their height is usually below five meters. Hence, for high elevation landscapes, separating forest/no forest was most challenging.

Cloud cover was an issue across all sites. Compared to North America, data density in Europe is still considerably lower (Wulder et al. 2016). This lower data density dramatically reduced the probability of acquiring cloud-free Landsat observations with similar phenological characteristics. We aimed to overcome this challenge by integrating data from the USGS and ESA archives to create robust median summer composites from all available observations across archives (Rufin et al. 2015). Missing years were filled using linear interpolation between observations from neighboring years (Hermosilla et al. 2015a). Nonetheless, we still had to adjust the time window for creating our median summer composites for the Tatra to achieve data densities high enough for spatially continuous analyses. Increasing the temporal window of acceptable observations introduced additional noise into the analysis, likely due to increased phenological variation, which might especially affect strongly climate-sensitive areas (e.g., high elevation areas in mountain regions) and regions with a higher share of deciduous trees. Frequent cloud cover (and frequent snow) also likely explain the higher disturbance commission errors in the higher-elevation sites (Berchtesgaden and Kalkalpen).

We experienced difficulties in determining the exact disturbance onset from Landsat time series, with only 60% of the disturbance onsets being identical to the onset estimated by visual interpretation. However, the percentage of correctly classified disturbance onsets increased to 80% when onsets that matched the reference date within ±1 years where included. This finding is similar to previous studies mapping annual forest disturbances of varying intensities in the USA (Kennedy et al. 2012a). Onset estimates were particularly variable for disturbances with long duration. It is challenging to determine an exact onset for those disturbances, because they are often caused by bark beetle infestations that slowly build up (Kautz 2014; Meigs et al. 2011). We hence acknowledge that the disturbance onset might be uncertain for many disturbances, and we suggest caution in its interpretation.

We here focussed on stand-replacing disturbances, defined as disturbances that reduce canopy cover in a pixel below 50%. Thus, we did not map ephemeral disturbances, such as insect defoliation (Senf et al. 2015) or water stress/drought (Assal et al. 2016). Including ephemeral disturbances of low spectral magnitude can substantially increase omission errors, since these are easily confused with noise from phenological variations and residual clouds (Cohen et al. 2017). Thinning – which is an often-applied management technique in the coupled human and natural systems of Central Europe – also results in relatively low intensity spectral changes (Jarron et al. 2016). We thus have largely omitted thinning operations in our analysis, as thinning intensities are usually below 50% in Central Europe (Seidl et al. 2017), and there is no substantial exposure of forest soil. Furthermore, multi-stage harvesting operations that aim at fostering natural regeneration (e.g., gap or shelterwood cuts) are also likely to be omitted by our analysis.

5.2 The effect of management on spatiotemporal dynamics of forest disturbances

Disturbance rates varied substantially among sites and management classes. Disturbance rates in strictly protected forests were lower than in protected and managed forests in the mountainous sites (Berchtesgaden and Kalkalpen). This result suggests that disturbance rates resulting from natural disturbances – in this case the combined effect of wind and bark beetle disturbances – are lower than disturbance rates resulting from management in the northern Alps. For the Bohemian Forest and Harz sites, however, highest disturbance rates were found in strictly protected forests. Both sites have seen large-scale outbreaks of bark beetles that affected large parts of the spruce-dominated strictly protected core zones. Hence, for those two sites we found that natural disturbances – in this case large-scale bark beetle outbreaks – resulted in higher disturbance rates than human and natural disturbances in the surrounding managed forests. This finding also suggests that for these regions proactive management to counter bark beetle outbreaks was successful relative to the natural development in strictly protected areas (Stadelmann et al. 2013).

Interestingly, disturbance rates in the management zones of national parks (i.e., here referred to as protected areas) were always higher than in managed forests, highlighting the combined effect of natural disturbances and reactive management. Indeed, in the coupled human and natural system of Central Europe, the strategy of many national parks not to manage bark beetle outbreaks in core zones has led to intensive public debate about natural disturbances, and increased the pressure on park authorities to prevent the spread of disturbance outside the park boundaries. As a consequence, many parks have established buffer zones between 100 m and 1,500 m to prevent bark beetle dispersal (Wermelinger 2004). The harvest operations in these dedicated buffer zones (i.e., salvage logging and sanitation felling), in combination with natural disturbance dynamics, likely explain the finding of high disturbance rates in these areas.

Forest disturbances in Central Europe are much smaller compared to previous studies in North America (Kennedy et al. 2012b; White et al. 2017). Smaller patch sizes result in a generally higher abundance of mixed pixels, likely affecting disturbance mapping accuracies. We applied a minimum mapping unit of 0.5 ha to reduce disturbance commission errors. By doing so, we might have omitted small disturbances, that is mortality of small patches of trees or small-scale felling in managed forests. Patch size distributions were not substantially different among the three management zones and across the five sites. Yet, patch sizes in the protected zones of the national parks were slightly higher than in strictly protected and managed forests. In the protected zones, we also found the overall largest patch sizes, both resulting from large-scale salvage operations after wind and bark beetle disturbances (Bohemian Forest and Tatra). Salvage operations often remove all vegetation including residual trees, leading to generally larger non-treed patches than in areas of natural disturbances alone (Lindenmayer and Noss 2006). Patch sizes in managed forests were, in turn, slightly larger than those in strictly protected forests. This result suggests that human management increases disturbance size relative to natural disturbances. However, for the two low mountain range sites we found opposite results (Bohemian Forest and Harz). Those two sites have experienced large-scale outbreaks of bark beetles, which have resulted in relatively large and continuous disturbances patches. Hence, in sites affected by more complex interactions of wind and bark beetles (Berchtesgaden, Kalkalpen, Tatra), natural disturbances were smaller than disturbances in managed forests. Whereas patches of natural disturbances were larger in sites affected by large-scale bark beetle outbreaks (Bohemian Forest and Harz).

Major storm events were a principal driver of disturbance dynamics throughout all sites, such as Kyrill in January 2007 and the Bora-type storm event affecting the Tatra mountains in December 2004. Both storms had by far the biggest impact on inter-annual variation in disturbance rates, with significant increases in disturbance rates during the storm years detected throughout all management classes. Yet, disturbance rates in managed forests dropped again rapidly after the storm events, while disturbance rates in protected and strictly protected forests showed a second increase in disturbance rates two to three years after the storm events. This finding suggests that in protected and strictly protected forests, where disturbances are allowed to progress without or with minimal human intervention, wind disturbances triggered a substantial eruption of subsequent bark beetle infestation. This finding is in congruence with observations and theoretical understanding, highlighting that storm events are a principal driver of bark beetle population dynamics in Central Europe (Seidl and Rammer 2016; Stadelmann et al. 2014; Wermelinger 2004).

We also found a consistent increase in disturbances rates in protected and strictly protected forests around 1995 for the Berchtesgaden, Bohemian Forest, and Harz sites. For the Bohemian Forest, this peak is the result of a large-scale outbreak of bark beetles at around this time (Kautz et al. 2011). Less information is available for the other sites, but we assume that bark beetle is the driver also there, as bark beetle population development tends to be synchronized across larger regions, e.g. as a result of regional drought (Seidl et al. 2016).

5.3 The effect of management on spectral-temporal disturbances characteristics

We found distinct differences in disturbance characteristics among the three management zones. In particular, we found that disturbances of natural agents (i.e., in strictly protected forests) were longer in duration, whereas human-dominated disturbances (i.e., in managed forests) were characterized by very short (one-year) disturbance duration. This reflects the general understanding that disturbances caused by insects and pathogens result in long-term spectral declines (Meigs et al. 2011; Vogelmann et al. 2009), while harvest disturbances generally result in very-short (one-year) spectral changes (Goodwin et al. 2008; Meigs et al. 2015). Our results thus demonstrate that the general notion of short (harvest) versus long (insect) disturbances also holds true for Central Europe, as has been suggested in an early case study on the Bohemian Forest (Hais et al. 2009).

However, many disturbances in strictly protected forests were not only caused by bark beetles, but also by wind. Hence, unmanaged wind disturbances also were of longer duration, challenging our prior assumption that wind disturbances always result in short-term spectral changes. Reasons for the longer duration related to wind disturbances might be the fact that blowdowns in the mountainous sites are often small in size (due to topographically related differences in wind exposure and soil rooting capacity), and do not necessarily uproot all trees within a stand, thus resulting in complex disturbance patches with uprooted and residual trees mixed at Landsat spatial resolution. Residual trees and trees on the edge of blowdowns are very susceptible to subsequent moderate winds and bark beetle infestation (Seidl and Rammer 2016; Stadelmann et al. 2014; Wermelinger 2004). Hence, unmanaged wind disturbances are likely mixed with secondary effects of subsequent wind events and bark beetle infestation, which results in longer spectral declines. One exception was the Tatra site, where disturbance durations in strictly protected areas dropped to one year following a major storm event in

2004. While the wind event of 2004 in the Tatra was extreme (gust wind speeds of 54 m s^{-1}) and differed meteorologically from the storms affecting the other sites (Bora-type wind vs. cyclonal storm), the drivers of different ecological patterns remain unresolved and should be addressed in future analyses.

Less pronounced differences were found regarding the spectral disturbance magnitude, with natural disturbances having similar median magnitudes as human-dominated disturbances. Yet, we found that maximum disturbance magnitudes were slightly higher for human-dominated disturbances. This finding is in agreement with earlier studies on wind (Baumann et al. 2014) and bark beetle disturbances (Hais et al. 2009), and reflects the contrasting ecological impacts of clearcut harvest disturbances (where virtually all biomass is removed from a site) and natural disturbances (where residual/understory vegetation, natural regeneration and deadwood remains onsite). However, we acknowledge that there is also a high proportion of low-severity disturbances in managed forests, highlighting that disturbance activity outside protected forests is the result of both natural and human agents. Furthermore, in many parts of Central Europe, small-scale harvests and thinning are preferred over large clearcut harvests, which is mirrored in the high abundance of small disturbance patches in our analysis. Consequently, even though we found distinct differences in the duration of natural and human disturbances, there is no clear distinction between natural and managed areas regarding the spectral magnitude of disturbances.

6. Conclusion

We here mapped forest disturbance patterns across five sites and three management zones in Central Europe using Landsat time series. We found that Landsat time series are suitable for mapping forest disturbances of varying agents in the coupled human and natural systems of Central Europe. Yet, we also highlighted some challenges in disturbance mapping, particularly regarding forests close to the tree line, as well as the correct determination of disturbance onset. We found that temporal disturbance dynamics were synchronized across different levels of human influence, with higher disturbance rates occurring in – and following after – years with large storm events. However, spectral-temporal disturbance characteristics among management zones were substantially different. In particular, we found that disturbances originating from natural agents were longer in duration and had lower peak spectral disturbance magnitudes. Disturbances in managed forests, originating from both human and natural agents, were short in duration and had higher peak spectral disturbance magnitudes. From those results, we conclude that remotely sensed natural disturbances in coupled human and natural systems are superimposed by a management signal (i.e., salvage and sanitation logging). This confounding factor potentially hampers the attribution of a formal change agent with current methods. Our study presents the first systematic assessment of forest disturbances across Central Europe, highlighting opportunities and challenges for future remote sensing-based analyses of forest disturbances in Europe.

Acknowledgements

We gratefully thank Andreas Rabe (Geography Department, Humboldt-Universität zu Berlin) for data processing support. The work leading to this publication was supported by the German Academic Exchange Service (DAAD) with funds from the German Federal Ministry of Education and Research (BMBF) and the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement Nr. 605728 (P.R.I.M.E. – Postdoctoral Researchers International Mobility Experience). D. Pflugmacher acknowledges funding from the German Federal Ministry of Education and Research through the GeoMultiSens project (01IS14010B). R. Seidl acknowledges support from a START grant of the Austrian Science Fund FWF (Y895-B25). This research contributes to the Landsat Science Team 2012-2017 (https://landsat.usgs.gov/2012-2017-science-team).

References

Assal, T.J., Anderson, P.J., & Sibold, J. (2016). Spatial and temporal trends of drought effects in a heterogeneous semi-arid forest ecosystem. *Forest Ecology and Management, 365*, 137-151

Baumann, M., Ozdogan, M., Wolter, P.T., Krylov, A., Vladimirova, N., & Radeloff, V.C. (2014). Landsat remote sensing of forest windfall disturbance. *Remote Sensing of Environment, 143*, 171-179

Bebi, P., Seidl, R., Motta, R., Fuhr, M., Firm, D., Krumm, F., Conedera, M., Ginzler, C., Wohlgemuth, T., & Kulakowski, D. (2017). Changes of forest cover and disturbance regimes in the mountain forests of the Alps. *Forest Ecology and Management, 388*, 43-56

Breiman, L. (2001). Random Forests. *Machine Learning, 45*, 5-32

Cohen, W., Healey, S., Yang, Z., Stehman, S., Brewer, C., Brooks, E., Gorelick, N., Huang, C., Hughes, M., Kennedy, R., Loveland, T., Moisen, G., Schroeder, T., Vogelmann, J., Woodcock, C., Yang, L., & Zhu, Z. (2017). How Similar Are Forest Disturbance Maps Derived from Different Landsat Time Series Algorithms? *Forests, 8*, 98

Cohen, W.B., & Goward, S.N. (2004). Landsat's role in ecological applications of remote sensing. *Bioscience, 54*, 535-545

Cohen, W.B., Yang, Z., & Kennedy, R. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync — Tools for calibration and validation. *Remote Sensing of Environment, 114*, 2911-2924

Cohen, W.B., Yang, Z., Stehman, S.V., Schroeder, T.A., Bell, D.M., Masek, J.G., Huang, C., & Meigs, G.W. (2016). Forest disturbance across the conterminous United States from 1985–2012: The emerging dominance of forest decline. *Forest Ecology and Management, 360*, 242-252

Crist, E.P. (1985). A TM Tasseled Cap Equivalent Transformation for Reflectance Factor Data. *Remote Sensing of Environment, 17*, 301-306

Cyr, D., Gauthier, S., Bergeron, Y., & Carcaillet, C. (2009). Forest management is driving the eastern North American boreal forest outside its natural range of variability. *Frontiers in Ecology and the Environment, 7*, 519-524

European Environmental Agency (2006). European forest types -Categories and types for sustainable forest management reporting and policy. In, *EEA Technical Reports*. Copenhagen: European Envieonmental Agency

Franklin, J.F., Spies, T.A., Pelt, R.V., Carey, A.B., Thornburgh, D.A., Berg, D.R., Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K., & Chen, J. (2002). Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. *Forest Ecology and Management, 155*, 399-423

Gao, F., Masek, J., & Wolfe, R.E. (2009). Automated registration and orthorectification package for Landsat and Landsat-like data processing. *Journal of Applied Remote Sensing, 3*, 033515-033515-033520

Goodwin, N.R., Coops, N.C., Wulder, M.A., Gillanders, S., Schroeder, T.A., & Nelson, T. (2008). Estimation of insect infestation dynamics using a temporal sequence of Landsat data. *Remote Sensing of Environment, 112*, 3680-3689

Griffiths, P., Kuemmerle, T., Baumann, M., Radeloff, V.C., Abrudan, I.V., Lieskovsky, J., Munteanu, C., Ostapowicz, K., & Hostert, P. (2014). Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites. *Remote Sensing of Environment, 151*, 72-88

Hais, M., Jonášová, M., Langhammer, J., & Kučera, T. (2009). Comparison of two types of forest disturbance using multitemporal Landsat TM/ETM+ imagery and field vegetation data. *Remote Sensing of Environment, 113*, 835-845

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., & Townshend, J.R. (2013). High-resolution global maps of 21st-century forest cover change. *Science, 342*, 850-853

Healey, S., Cohen, W., Zhiqiang, Y., & Krankina, O. (2005). Comparison of Tasseled Cap-based Landsat data structures for use in forest disturbance detection. *Remote Sensing of Environment, 97*, 301-310

Hermosilla, T., Wulder, M.A., White, J.C., Coops, N.C., & Hobart, G.W. (2015a). An integrated Landsat time series protocol for change detection and generation of annual gap-free surface reflectance composites. *Remote Sensing of Environment, 158*, 220-234

Hermosilla, T., Wulder, M.A., White, J.C., Coops, N.C., & Hobart, G.W. (2015b). Regional detection, characterization, and attribution of annual forest change from 1984 to 2012 using Landsat-derived time-series metrics. *Remote Sensing of Environment, 170*, 121-132

Jarron, L., Hermosilla, T., Coops, N., Wulder, M., White, J., Hobart, G., & Leckie, D. (2016). Differentiation of Alternate Harvesting Practices Using Annual Time Series of Landsat Data. *Forests, 8*, 15

Kautz, M. (2014). On correcting the time-lag bias in aerial-surveyed bark beetle infestation data. *Forest Ecology and Management, 326*, 157-162

Kautz, M., Dworschak, K., Gruppe, A., & Schopf, R. (2011). Quantifying spatio-temporal dispersion of bark beetle infestations in epidemic and non-epidemic conditions. *Forest Ecology and Management, 262*, 598-608

Kennedy, R.E., Andréfouët, S., Cohen, W.B., Gómez, C., Griffiths, P., Hais, M., Healey, S.P., Helmer, E.H., Hostert, P., Lyons, M.B., Meigs, G.W., Pflugmacher, D., Phinn, S.R., Powell, S.L., Scarth, P., Sen, S., Schroeder, T.A., Schneider, A., Sonnenschein, R., Vogelmann, J.E., Wulder, M.A., & Zhu, Z. (2014). Bringing an ecological view of change to Landsat-based remote sensing. *Frontiers in Ecology and the Environment, 12*, 339-346

Kennedy, R.E., Yang, Z., Cohen, W.B., Pfaff, E., Braaten, J., & Nelson, P. (2012a). Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan. *Remote Sensing of Environment, 122*, 117-133

Kennedy, R.E., Yang, Z.Q., Cohen, W.B., Pfaff, E., Braaten, J., & Nelson, P. (2012b). Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan. *Remote Sensing of Environment, 122*, 117-133

Kulakowski, D., Seidl, R., Holeksa, J., Kuuluvainen, T., Nagel, T.A., Panayotov, M., Svoboda, M., Thorn, S., Vacchiano, G., Whitlock, C., Wohlgemuth, T., & Bebi, P. (2017). A walk on the wild side: Disturbance dynamics and the conservation and management of European mountain forest ecosystems. *Forest Ecology and Management, 388*, 120-131

Levers, C., Verkerk, P.J., Müller, D., Verburg, P.H., Butsic, V., Leitão, P.J., Lindner, M., & Kuemmerle, T. (2014). Drivers of forest harvesting intensity patterns in Europe. *Forest Ecology and Management, 315*, 160-172

Lindenmayer, D.B., Burton, P.J., & Franklin, J.F. (2012). *Salvage logging and its ecological consequences*. Island Press

Lindenmayer, D.B., & Noss, R.F. (2006). Salvage Logging, Ecosystem Processes, and Biodiversity Conservation. *Conservation Biology, 20*, 949-958

Masek, J.G., Vermote, E.F., Saleous, N.E., Wolfe, R., Hall, F.G., Huemmrich, K.F., Feng, G., Kutler, J., & Teng-Kui, L. (2006). A Landsat surface reflectance dataset for North America, 1990-2000. *Geoscience and Remote Sensing Letters, IEEE, 3*, 68-72

McDowell, N.G., Coops, N.C., Beck, P.S., Chambers, J.Q., Gangodagamage, C., Hicke, J.A., Huang, C.Y., Kennedy, R., Krofcheck, D.J., Litvak, M., Meddens, A.J., Muss, J., Negron-Juarez, R., Peng, C., Schwantes, A.M., Swenson, J.J., Vernon, L.J., Williams, A.P., Xu, C., Zhao, M., Running, S.W., & Allen, C.D. (2015). Global satellite monitoring of climate-induced vegetation disturbances. *Trends Plant Sci, 20*, 114-123

Meigs, G.W., Kennedy, R.E., & Cohen, W.B. (2011). A Landsat time series approach to characterize bark beetle and defoliator impacts on tree mortality and surface fuels in conifer forests. *Remote Sensing of Environment, 115*, 3707-3718

Meigs, G.W., Kennedy, R.E., Gray, A.N., & Gregory, M.J. (2015). Spatiotemporal dynamics of recent mountain pine beetle and western spruce budworm outbreaks across the Pacific Northwest Region, USA. *Forest Ecology and Management, 339*, 71-86

Moisen, G.G., Meyer, M.C., Schroeder, T.A., Liao, X., Schleeweis, K.G., Freeman, E.A., & Toney, J.C. (2016). Shape selection in Landsat time series: A tool for monitoring forest dynamics. *Global Change Biology*, n/a-n/a

Munteanu, C., Kuemmerle, T., Keuler, N.S., Müller, D., Balázs, P., Dobosz, M., Griffiths, P., Halada, L., Kaim, D., Király, G., Konkoly-Gyuró, É., Kozak, J., Lieskovsky, J., Ostafin, K., Ostapowicz, K., Shandra, O., & Radeloff, V.C. (2015). Legacies of 19th century land use shape contemporary forest cover. *Global Environmental Change, 34*, 83-94

Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E., & Wulder, M.A. (2014). Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment, 148*, 42-57

Parviainen, J. (2005). Virgin and natural forests in the temperate zone of Europe. *Forest Snow and Landscape Research, 79*, 9-18

Parviainen, J., & Frank, G. (2003). Protected forests in Europe approaches-harmonising the definitions for international comparison and forest policy making. *J Environ Manage, 67*, 27-36

Pflugmacher, D., Cohen, W.B., & E. Kennedy, R. (2012). Using Landsat-derived disturbance history (1972–2010) to predict current forest structure. *Remote Sensing of Environment, 122*, 146-165

Potapov, P.V., Turubanova, S.A., Tyukavina, A., Krylov, A.M., McCarty, J.L., Radeloff, V.C., & Hansen, M.C. (2015). Eastern Europe's forest cover dynamics from 1985 to 2012 quantified from the full Landsat archive. *Remote Sensing of Environment, 159*, 28-43

Rufin, P., Müller, H., Pflugmacher, D., & Hostert, P. (2015). Land use intensity trajectories on Amazonian pastures derived from Landsat time series. *International Journal of Applied Earth Observation and Geoinformation, 41*, 1-10

Schelhaas, M.-J., Nabuurs, G.-J., & Schuck, A. (2003). Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology, 9*, 1620-1633

Seidl, R., Muller, J., Hothorn, T., Bassler, C., Heurich, M., & Kautz, M. (2016). Small beetle, large-scale drivers: how regional and landscape factors affect outbreaks of the European spruce bark beetle. *J Appl Ecol, 53*, 530-540

Seidl, R., & Rammer, W. (2016). Climate change amplifies the interactions between wind and bark beetle disturbances in forest landscapes. *Landscape Ecology*

Seidl, R., Schelhaas, M.-J., & Lexer, M.J. (2011). Unraveling the drivers of intensifying forest disturbance regimes in Europe. *Global Change Biology, 17*, 2842-2852

Seidl, R., Schelhaas, M.J., Rammer, W., & Verkerk, P.J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. *Nat Clim Chang, 4*, 806-810

Seidl, R., Vigl, F., Rössler, G., Neumann, M., & Rammer, W. (2017). Assessing the resilience of Norway spruce forests through a model-based reanalysis of thinning trials. *Forest Ecology and Management, 388*, 3-12

Senf, C., Pflugmacher, D., Heurich, M., & Krueger, T. (2017). A Bayesian hierarchical model for estimating spatial and temporal variation in vegetation phenology from Landsat time series. *Remote Sensing of Environment, 194*, 155-160

Senf, C., Pflugmacher, D., Wulder, M.A., & Hostert, P. (2015). Characterizing spectral–temporal patterns of defoliator and bark beetle disturbances using Landsat time series. *Remote Sensing of Environment, 170*, 166-177

Stadelmann, G., Bugmann, H., Meier, F., Wermelinger, B., & Bigler, C. (2013). Effects of salvage logging and sanitation felling on bark beetle (Ips typographus L.) infestations. *Forest Ecology and Management, 305*, 273-281

Stadelmann, G., Bugmann, H., Wermelinger, B., & Bigler, C. (2014). Spatial interactions between storm damage and subsequent infestations by the European spruce bark beetle. *Forest Ecology and Management, 318*, 167-174

Thomas, N.E., Huang, C.Q., Goward, S.N., Powell, S., Schleeweis, K., & Hinds, A. (2011). Validation of North American Forest Disturbance dynamics derived from Landsat time series stacks. *Remote Sensing of Environment, 115*, 19-32

Thorn, S., Bassler, C., Gottschalk, T., Hothorn, T., Bussler, H., Raffa, K., & Muller, J. (2014). New insights into the consequences of post-windthrow salvage logging revealed by functional structure of saproxylic beetles assemblages. *Plos One, 9*, e101757

Turner, M.G. (2010). Disturbances and landscape dynamics in a changing world. *Ecology, 91*, 2833-2849

Vermote, E., Justice, C., Claverie, M., & Franch, B. (2016). Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote Sensing of Environment, 185*, 46-56

Vogelmann, J.E., Tolk, B., & Zhu, Z.L. (2009). Monitoring forest changes in the southwestern United States using multitemporal Landsat data. *Remote Sensing of Environment, 113*, 1739-1748

Wermelinger, B. (2004). Ecology and management of the spruce bark beetle Ips typographus—a review of recent research. *Forest Ecology and Management, 202*, 67-82

White, J.C., Wulder, M.A., Hermosilla, T., Coops, N.C., & Hobart, G.W. (2017). A nationwide annual characterization of 25 years of forest disturbance and recovery for Canada using Landsat time series. *Remote Sensing of Environment, 194*, 303-321

Wulder, M.A., Masek, J.G., Cohen, W.B., Loveland, T.R., & Woodcock, C.E. (2012). Opening the archive: How free data has enabled the science and monitoring promise of Landsat. *Remote Sensing of Environment, 122*, 2-10

Wulder, M.A., White, J.C., Bentz, B., Alvarez, M.F., & Coops, N.C. (2006). Estimating the probability of mountain pine beetle red-attack damage. *Remote Sensing of Environment, 101*, 150-166

Wulder, M.A., White, J.C., Loveland, T.R., Woodcock, C.E., Belward, A.S., Cohen, W.B., Fosnight, E.A., Shaw, J., Masek, J.G., & Roy, D.P. (2016). The global Landsat archive: Status, consolidation, and direction. *Remote Sensing of Environment, 185*, 271-283

Zhu, Z., & Woodcock, C.E. (2012). Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment, 118*, 83-94

Appendix

Table A1: Summary of the reference data collected for calibrating (Cal.) and validating (Val.) the disturbance classification.

Number of samples	Site									
	Berchtesgaden		Bohemian Forests		Harz		Kalkalpen		Tatra	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
Total	251	249	236	264	225	275	246	254	242	258
Non-forested	100	92	55	59	80	86	55	56	96	119
Forested	149	153	180	202	135	176	190	192	142	132
Disturbed	66	64	103	113	70	88	87	102	76	67
Undisturbed	83	88	77	88	63	86	101	89	66	63
Not interpretable	2	5	1	4	2	3	3	7	4	9