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Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites

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A B S T R A C T

Detailed knowledge of forest cover dynamics is crucial for many applications from resource management to ecosystem service assessments. Landsat data provides the necessary spatial, temporal and spectral detail to map and analyze forest cover and forest change processes. With the opening of the Landsat archive, new opportunities arise to monitor forest dynamics on regional to continental scales. In this study we analyzed changes in forest types, forest disturbances, and forest recovery for the Carpathian ecoregion in Eastern Europe. We generated a series of image composites at five year intervals between 1985 and 2010 and utilized a hybrid analysis strategy consisting of radiometric change classification, post-classification comparison and continuous index- and segment-based post-disturbance recovery assessment. For validation of the disturbance map we used a point-based accuracy assessment, and assessed the accuracy of our forest type maps using forest inventory data and statistically sampled ground truth data for 2010. Our Carpathian-wide disturbance map achieved an overall accuracy of 86% and the forest type maps up to 73% accuracy. While our results suggested a small net forest increase in the Carpathians, almost 20% of the forests experienced stand-replacing disturbances over the past 25 years. Forest recovery seemed to only partly counterbalance the widespread natural disturbances and clear-cutting activities. Disturbances were most widespread during the late 1980s and early 1990s, but some areas also exhibited extensive forest disturbances after 2000, especially in the Polish, Czech and Romanian Carpathians. Considerable shifts in forest composition occurred in the Carpathians, with disturbances increasingly affecting coniferous forests, and a relative decrease in coniferous and mixed forests. Both aspects are likely connected to an increased vulnerability of spruce plantations to pests and pathogens in the Carpathians. Overall, our results exemplify the highly dynamic nature of forest cover during times of socio-economic and institutional change, and highlight the value of the Landsat archive for monitoring these dynamics.

1. Introduction

Globally, forests provide important resources and ecosystem services that are essential for human well-being, including timber and non-timber forest product provision, watershed protection, habitat for biodiversity, and recreational amenities (GLP, 2005; Millennium Ecosystem Assessment, M.A, 2005). Similarly, the role of forests for climate regulation, carbon sequestration, and surface radiation modulation is of global importance (IPCC, 2000). However, forest resources and related ecosystem services depend on forest type and composition as well as on forest condition and management (e.g. rotation interval, mechanization, fertilizer use, plantation schemes), making it paramount to monitor forests repeatedly and consistently across larger areas and with high spatial detail.

Remote sensing has long been instrumental for mapping and monitoring forest cover changes and it was satellite imagery that highlighted widespread deforestation in the world's tropical regions (Pfaff, 1999; Skole & Tucker, 1993). In contrast though, forest area is increasing in many developed nations due to combined effects of advances in agricultural productivity and increasing awareness regarding the environmental importance of forests (Lambin & Meyfroidt, 2010; Meyfroidt & Lambin, 2011). However, information on forests and forest cover changes are not always publicly accessible and we still lack comprehensive knowledge of spatio-temporally explicit forest cover dynamics,

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especially across large areas and with sufficient spatial detail to resolve the full range of forest change processes.

Knowing forest area alone does not suffice. In many regions, natural primary forest is or has been converted to plantations and secondary forests. While the total forest area may remain stable or even increase, such forest types often do not provide the ecological services provided by natural forests (FAO, 2005). Last but not least, the disturbance regime is crucial for ecological functioning, with related spatial disturbance patterns and frequencies being equally important to understand if natural disturbance regimes persist or have been replaced by forest harvesting.

Remote sensing has established itself as the key technology for forest mapping and monitoring at different spatial and temporal scales. Sensor systems such as the Moderate Resolution Imaging Spectrometer (MODIS) enable global forest monitoring and can be used to map broad-scale changes in temperate forests (Potapov, Hansen, Stehman, Pittman, & Turubanova, 2009), but are limited in their ability to provide detailed information on forest composition changes or fine-scale forest change processes. Data from the Landsat sensors, on the other hand, provide spatial and spectral detail that allows capturing forest attributes at adequate scales, while featuring archived data back to the early 1970s. When working over larger geographical extents (i.e., ecoregions, biomes or continents) at 30 m spatial resolution, however, Landsat data analysis poses numerous challenges. The sensor-specific field-of-view and the resulting scene coverage, coupled with frequent cloud cover and phenological effects due to the timing of image acquisitions, require specific conceptual frameworks to allow for adequate mapping and monitoring over larger areas. The opening of the USGS Landsat archive in 2008 sparked many new algorithms in this respect. Continental or even global Landsat data analyses are now feasible as advanced and automated preprocessing methods as well as improved processing and data storage capabilities allow for mass processing of imagery (Townshend et al., 2012; Wulder, Masek, Cohen, Loveland, & Woodcock, 2012).

One approach to better exploit the wealth of Landsat images with partial cloud cover is pixel-based compositing methods, which combine several images into one cloud-free composite (Potapov, Turubanova, & Hansen, 2011; Roy et al., 2010). Compositing algorithms were initially developed for wide-swath sensor data, where observations are very frequent, but no image is ever completely cloud-free, and reducing cloud contamination and other atmospheric effects is therefore essential (Cihlar, Manak, & Diorio, 1994; Holben, 1986). For Landsat data, compositing offers comparable advantages, though. By selecting the best observation on a per-pixel basis, cloudy imagery (typically discarded within scene-based approaches) can be exploited for high quality observations and the 16-day repeat cycle can be overcome through utilization of the across track overlap between adjacent image acquisition paths, which is considerable at higher latitudes. A single, "global" classification/regression model can be trained and applied if composites have sufficient seasonal and radiometric consistency, making large area mapping and monitoring approaches with Landsat more practicable.

Initial attempts to composite Landsat data were made during the generation of the Global Land Survey 2005 dataset (Gutman et al., 2008). Compositing was then used to fill data gaps in ETM+ imagery due to the failure of the scan line corrector since May 2003 (Arvidson, Goward, Gasch, & Williams, 2006). Compositing has also been implemented to allow broad-scale deforestation mapping. Hansen et al. (2008), for example, produced two regional Landsat composites for change detection in the Congo basin and incorporated the MODIS Vegetation Continuous Field product (Hansen et al., 2003) for training of the classifiers. Potapov et al. (2011) studied boreal forest changes between 2000 and 2005 in European Russia using composited Landsat data and achieved high agreement with independently derived samples of forest change. Both studies demonstrated the ability of Landsat imagery for wall-to-wall mapping and regional monitoring of forest cover changes. Thus, Landsat image compositing has so far greatly advanced regional forest mapping and monitoring with a focus on reporting changes in forest extents. It is therefore desirable to advance remote sensing based methods towards analyzing spatio-temporal patterns of forest types, disturbance and recovery regimes across large areas. Also, more applications in diverse forested regions of the world are necessary to advance compositing and related algorithms, and to better assess their potential and limitations.

In this study, we utilize a series of large-area composites to map forest disturbances, forest recovery, and changes in forest types in a temperate forest region, the Carpathian ecoregion in Eastern Europe. The forests in the Carpathian Mountains represent Europe's largest temperate forest ecosystem and are of exceptional ecological value, providing resources and ecological services to a region much larger than the Carpathians themselves. Carpathian forests have been exploited and managed for centuries, leading to the widespread conversion of natural forests (i.e., beech-dominated, deciduous and mixed forests) to monoculture plantations of Norway spruce (Keeton & Crow, 2009; UNEP, 2007). These spruce plantations are highly susceptible to pest outbreaks and storm damages, and during the last decades forest managers are increasingly converting them to more natural forest types (Keeton & Crow, 2009). The remaining semi-natural and old-growth forests, on the other hand, are threatened by the major socio-economic restructuring processes that occurred with the transition from state-led to market-oriented economy after the collapse of Eastern European socialism (Hostert et al., 2011; Knorn, Kuemmerle, Radeloff, Szabo, et al., 2012; Kuemmerle, Chaskovskyy, et al., 2009; Kuemmerle, Kozak, Radeloff, & Hostert, 2009). This highlights the importance to analyze forest dynamics across the entire Carpathians.

Accordingly, our goal here was to map forest disturbances and change in forest types across the Carpathian region from 1985 to 2010 using Landsat satellite images, applying automated image preprocessing and compositing as well as a hybrid change detection approach. Our specific research questions were:

- How were broad forest types distributed in the Carpathians at the end of the socialist period and how did this distribution change over time?
- What were the rates and spatial and temporal patterns of forest disturbances since 1985?
- What were the spatio-temporal patterns of post-disturbance forest recovery?

The results of this study are publicly available (see http://www.hu-geomatics.de).

2. Methods

2.1. Study area

We studied the Carpathian mountain range in Central Eastern Europe. The study region boundaries were based on the Carpathian Ecoregion Initiative (CERI) boundaries (CERI, 2001) and were extended to include adjacent administrative units in their entirety (Nomenclature of Territorial Units for Statistics (NUTS) level three, and oblasts in the case of Ukraine). The study region covered 390,000 km^2 including parts of the Czech Republic, Austria, Poland, Hungary, Ukraine, Romania and all of Slovakia (Fig. 1). The total population of the Carpathian ecoregion is around 17 million (CERI, 2001). The Carpathians extend in a curve shaped arc over a length of about 1500 km at a maximal width of 350 km. Elevations reach 2600 m in the Tatra Mountains in Poland and Slovakia, and 2500 m in the FăgăraŞ Mountains in Romania. The region is characterized by a temperate continental climate. Precipitation ranges from 400 mm in the southeastern parts to over 2000 mm at the highest elevations (Ptacek, Letal, Ruffini, & Renner, 2009). Annual average temperatures vary with elevation and are about 2 °C around mid-elevations (UNEP, 2007).

Forests cover between 50% and 60% of the Carpathian ecoregion and approximately 30% of the region is used for agriculture (Ruffini, Hoffmann, Streifeneder, & Renner, 2008). The most common tree species are European beech (Fagus sylvatica), Norway spruce (*Picea abies*) and silver fir (*Abies alba*). Natural forest types follow a vertical