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Monitoring coniferous forest biomass change using a Landsat trajectory-based approach

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ABSTRACT

Forest biomass is a major store of carbon and thus plays an important role in the regional and global carbon cycle. Accurate forest carbon sequestration assessment requires estimation of both forest biomass and forest biomass dynamics over time. Forest dynamics are characterized by disturbances and recovery, key processes affecting site productivity and the forest carbon cycle. Thus, spatially and temporally explicit knowledge of these processes and their drivers are critical for understanding regional carbon cycles. Here, we present a new method that uses satellite data to estimate changes in forest aboveground biomass associated with forest disturbances and recovery at annual time steps. First, yearly maps of aboveground biomass between 1985 and 2010 based on Landsat time series and field data were created. Then, we applied a trajectory-based segmentation and fitting algorithm to the yearly biomass maps to reconstruct the forest disturbance and recovery history over the last 25 years.

We tested the method over a coniferous forest region in the Western Carpathian Mountains, which experienced long-term environmental changes. Overall, 55% (~30,700 ha) of the total coniferous forest experienced a loss of biomass over the observation period, while ~30% showed severe or complete removal of forest biomass. At the same time, 11.2% of the area was reforested or regenerated on previously damaged forest stands. The total coniferous biomass dropped by 15% between 1985 and 2010, indicating negative balance between the losses and the gains. Disturbance hotspots indicate high insect infestation levels in many areas and reveal strong interactions between biomass loss and climate conditions. Our study demonstrates how spatial and temporal estimates of biomass help to understand regional forest dynamics and derive degradation trends in regard to regional climate change.

1. Introduction

Forests store large amounts of carbon and play an important role in the regional and global carbon cycle. Accurate estimates of forest biomass dynamics require accounting for the spatial effects of disturbances and recovery, both affecting forest carbon emissions. The spatial extent and the magnitude of disturbance and regrowth determine the net carbon flux of a forest and the magnitude of carbon loss during and after disturbance (Frolking et al., 2009; Luyssaert Luyssaert et al., 2010). Disturbances can convert forests from a net carbon sink to a net carbon source (during and after the disturbance occurred) (Kurz, Dymond, et al., 2008; Kurz, Stinson, Rampley, Dymond and Neilson, 2008). Because productivity varies considerably by ecoregion and forest type, accurately estimating the mass of living forest material and its changes is critical especially for regional scale carbon models (Kimball, Keyser, Running, & Saatchi, 2000; Schroeder, Gray, Harmon, Wallin, & Cohen, 2008). Remote sensing data and their derivatives provide unique and appropriate input information to assess changes in forest biomass across different spatial and temporal scales (Mickler, Earnhardt, & Moore, 2002; Powell et al., 2010). Here we present a method to estimate and monitor aboveground forest biomass changes with near-annual time-series data.

Forest disturbance and recovery are key processes in forest ecosystem dynamics. Recovery is the reestablishment of a new forest stand or the regeneration of a partially disturbed stand following a previous disturbance. Disturbances occur due to management activities (e.g., harvest), and/or due to abiotic (e.g., windstorm) or biotic (insect pests, diseases) factors. From a management perspective, natural forest disturbances are often considered to cause unforeseen loss of forest biomass or to decrease the actual or potential value of forest stands (Schelhaas, Nabuurs, & Schuck, 2003). However, from an ecological perspective, a natural disturbance is merely a cyclical stage of forest *destruction–creation* dynamics (Moran & Ostrom, 2005; Rull, 2011). The dominant natural disturbance agents in European forests are storm events (53%), fires (16%) and biotic factors (e.g., pest, 16%) (Schelhaas et al., 2003).

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The Carpathian Mountains sustain Europe's largest continuous forest ecosystem, and are a bridge between Europe's southern and northern forests, serving as an important refuge and corridor for flora and fauna. Carpathian forests provide high biodiversity and productivity, and are a key element of the European carbon cycle (Schulp, Nabuurs, & Verburg, 2008). However, these forests have been influenced by humans for many centuries. During the Austro-Hungarian Empire and expansion of the industrial revolution in the mid-19th century, the demand for energy and fuel increased. As a consequence, exponentially increasing demand for softwood and its products triggered the beginning of regular forest management. Tree species ensuring high productivity, short harvesting cycle and quick revenues were propagated. Thus, most of the natural mountain hardwood and mixed forest stands have been replaced by conifer species, particularly by the productive and "cost-effective" Norway spruce [*Picea abies* (L.) Karst.] (Grodzińska & Szarek-Łukaszewska, 1997; Matiakowska & Szabla, 2007; Turnock, 2002).

In the second half of the 20th century, rapid industrialization, and inadequate environmental regulations led to increased environmental pollution in Central Europe (Csóka, 2005). Long-term critical atmospheric deposition of sulphur and nitrogen caused acidification and eutrophication of ecosystems leading to widespread deterioration of forest health and a diminished resistance to diverse stressors (Kubikova, 1991; Materna, 1989; Schulze, 1989). With the fall of communism in 1989, a phase of institutional and socio-economic changes begun, having direct and indirect impact on Carpathian forests. Direct impact has been observed for instance in Romania, where logging rates triggered by forest privatization and restitution increased (Griffiths et al., 2012; Knorn et al., 2012). Indirect effects linked to forest management and pollution legacies over the last 30 years caused widespread forest decline in the Carpathians (Kubikova, 1991; Main-Knorn, Hostert, Kozak, & Kuemmerle, 2009; Muzika, Guyette, Zielonka, & Liebhold, 2004). Particularly since the late 1990s, forest degradation and mortality of spruce stands reportedly increased in the Western Carpathians (Badea et al., 2004; Grodzki et al., 2004; Kozak, 1996), followed by a decline of forest area at present (Ditmarová, Kmet', Ježík, & Váľka, 2007; Durło, 2010; Grodzki, 2007; Šrámek, Vejpustková, Novotný, & Hellebrandová, 2008). Present forest disturbances in this area result predominantly from the coincidental effects of fungal pathogens (*Armillaria* spp.), unfavorable weather conditions, extreme storm events, and subsequent bark beetle (mainly *Ips typographus* (L.)) outbreaks. Moreover, the observed degradation of spruce stands in the Western Carpathians due to storm events and biotic factors (e.g., insect outbreaks) is expected to increase with climate change in the future (Hlásny, Fabrika, et al., 2010). Thus, assessing the spatial and temporal patterns of disturbances enables determination of past and present degradation and recovery, their long-term trends and potential effect on the carbon balance. It could also improve regional-scale carbon models, provide an important input to model possible impacts of climate change on spruce-dominated forests and underpin new paradigms for management strategies by local and regional policy makers.

As forest biomass dynamics are characterized by disturbances and subsequent recovery processes, the quantification of biomass variability over space and time is critical for accurate carbon accounting (Houghton, 2005). If available, forest inventories based on plot measurements provide biomass estimates with high precision, but these inventory-based approaches are spatially and temporally sparse (Houghton, 2005). Inventories in the Carpathians are designed to provide estimates at the scale of administrative units and for 10-year time intervals. Thus, they are often too coarse in space and time to represent disturbance-induced changes in biomass. Since the net carbon flux of a forest and the magnitude of carbon loss and uptake are determined by the rate of biomass change (reduction or accumulation) at fine spatial and temporal scales, only satellite data can adequately capture its dynamics over larger areas (Huang et al., 2010; Powell et al., 2010; Wulder, White, Coops, & Butson, 2008). Moreover, using time series of remote sensing data both continuous and subtle (associated with forest degradation or recovery) as well as discontinuous and sudden (e.g., clear-cuts, wind-throws) forest change phenomena can be assessed, quantified and monitored (Kennedy, Cohen, & Schroeder, 2007).

The Landsat satellites provide a unique, continuous record of earth observations at ample spatial and spectral resolution since 1972 and, hence, are well-suited for long-term forest change analyses (Cohen & Goward, 2004; Kennedy, Yang, & Cohen, 2010). Moreover, since the recent opening of the Landsat archive by the United States Geological Survey (USGS), new methodological approaches have emerged that make use of annual Landsat time series (Huang et al., 2010; Kennedy et al., 2010). Kennedy et al. (2010) developed a trajectory-based segmentation and fitting method: the Landsat-based detection of Trends in Disturbance and Recovery (LandTrendr), which can be used to reconstruct the disturbance history of forest stands at annual resolution. Unique to LandTrendr is that it detects and describes abrupt disturbances (e.g. fire and harvest) as well as long-term vegetation trends (e.g. regrowth and defoliation). Meigs, Kennedy, and Cohen (2011) applied the LandTrendr algorithm to characterize the impact of insect calamities on tree mortality. In other studies, annual disturbance history trajectories were used to predict forest structure (Pflugmacher, Cohen, & Kennedy, 2012; Pflugmacher, Cohen, Kennedy, & Yang, 2013), and to investigate the effects of institutional and ownership changes on forest resources (Griffiths et al., 2012). Recently, Powell et al. (2010) used LandTrendr to quantify live aboveground forest biomass dynamics at two forested sites in the United States. The authors applied the LandTrendr fitting approach to assess trajectories of biomass change and to reduce inter-annual noise in Landsat-based biomass predictions. The main outcome from this study was that the consistency of Landsat data through time and space made it possible to accurately monitor and quantify trends in biomass.

In a previous study, Main-Knorn et al. (2011) estimated forest biomass in the Western Carpathian Mountains for a single date with satellite and inventory data. Here, we build on the findings of this study and model historic biomass dynamics for the same region at near-annual time steps. To construct near-annual time series, we used imagery from Landsat, Satellite Pour l'Observation de la Terre (SPOT) and Indian Remote Sensing Satellite with the Linear Imaging Self-Scanning Sensor (IRS LISS). Then we use the LandTrendr algorithm to detect and describe biomass trends between 1985 and 2010. The objectives of our study were 1) to map abrupt and gradual disturbances, and forest recovery in the spruce-dominated forests of the Western Carpathian Mountains, 2) to quantify biomass losses and gains associated with these processes, and 3) to quantify the net change in forest biomass within the observation period.

2. Study area

The study area covers ~116,000 ha of forested land in the Beskid Mountains of the northwestern Carpathian Mountain Range (Fig. 1). Here, we focused on coniferous forests which encompass ~56,000 ha of the total forested area. Elevations in the study region extend up to 1550 m above sea level in the Beskid Żywiecki Massif. The climate is typical for moderate continental mountain zones with an annual precipitation of 1200 mm (Durło, 2010). The yearly mean temperature is about 7 °C below 700 m and about 4 °C at 1100 m. The dominant wind directions are western, south- and northwestern, with the highest speed between November and March potentially causing great damage to forest stands (Barszcz & Małek, 2008). Warm foehn winds from the south and southwest as well as temperature inversion in valleys are important aspects of the regional climate.

The dominating forest types are Norway spruce monocultures and mixed spruce stands with the admixture of European beech (*Fagus sylvatica*) and European silver fir (*Abies alba*) (Barszcz & Małek, 2008). As a result of ongoing stand conversion, some lower elevations feature mixed beech forests along with spruce and fir.