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Eastern Europe's forest cover dynamics from 1985 to 2012 quantified from the full Landsat archive

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ABSTRACT

In the former "Eastern Bloc" countries, there have been dramatic changes in forest disturbance and forest recovery rates since the collapse of the Soviet Union, due to the transition to open-market economies, and the recent economic crisis. Unfortunately though, Eastern European countries collected their forest statistics inconsistently, and their boundaries have changed, making it difficult to analyze forest dynamics over time. Our goal here was to consistently quantify forest cover change across Eastern Europe since the 1980s based on the Landsat image archive. We developed an algorithm to simultaneously process data from different Landsat platforms and sensors (TM and ETM+) to map annual forest cover loss and decadal forest cover gain. We processed 59,539 Landsat images for 527 footprints across Eastern Europe and European Russia. Our results were highly accurate, with gross forest loss producer's and user's accuracy of >88% and >89%, respectively, and gross forest gain producer's and user's accuracy of >75% and >91%, based on a sample of probability-based validation points. We found substantial changes in the forest cover of Eastern Europe. Net forest cover increased from 1985 to 2012 by 4.7% across the region, but decreased in Estonia and Latvia. Average annual gross forest cover loss was 0.41% of total forest cover area, with a statistically significant increase from 1985 to 2012. Timber harvesting was the main cause of forest loss, accompanied by some insect defoliation and forest conversion, while only 7.4% of the total forest cover loss was due to large-scale wildfires and windstorms. Overall, the countries of Eastern Europe experienced constant levels or declines in forest loss after the collapse of socialism in the late 1980s, but a pronounced increase in loss in the early 2000s. By the late 2000s, however, the global economic crisis coincided with reduced timber harvesting in most countries, except Poland, Czech Republic, Slovakia, and the Baltic states. Most forest disturbance did not result in a permanent forest loss during our study period. Indeed, forest generally recovered fast and only 12% of the areas of forest loss prior to 1995 had not yet recovered by 2012. Our results allow national and sub-national level analysis and are available on-line (http://glad.geog.umd.edu/europe/) to serve as a baseline for further analyses of forest dynamics and its drivers.

1. Introduction

European forests co-evolved with humans since the beginning of the Holocene, and their current distribution, structure, and dynamics represent a long history of clearing, alteration, and management (Fuchs, Herold, Verburg, & Clevers, 2013; Johann, 2004; Kalyakin et al., 2004; Kaplan, Krumhardt, & Zimmermann, 2009, 2012). Shaped by human activities, forests were a main sector of the economy providing food (e.g., hunting, livestock grazing, and plant products), timber products (e.g., lumber for construction and naval fleets, and pulp for paper), fuel (e.g., firewood, and charcoal), and other important resources (e.g., potash, and tar). The importance of forest resources, which can be quickly exhausted by unrestricted use, provided the impetus for forest mapping, inventory, and management. Forest mapping techniques were developed concomitantly with land tenure systems, and the first forest maps were already produced in the 14th century (Morse, 2007). In North and Central Europe, exhaustion of timber resources for naval ship building, lumber, and charcoal used for iron production, were the main factors why forest inventories were established in the 19th century (Eliasson, 2002; Tomppo, Gschwantner, Lawrence, & McRoberts, 2010). Forest inventories and management expanded into Eastern Europe and European Russia in the 19th and 20th centuries. In the 20th century, national forest inventory and monitoring incorporated various instrumental measurement methods, statistical sampling, and, later, remote sensing technology. As a result, the forests of Europe are among the most well-monitored ecosystems of the world.

Despite the wealth of forest inventory data, this information is unfortunately not readily available, nor well suited for region-wide analyses. One problem is that forest definitions and inventory methods

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vary among countries and have changed over time, making cross-national and multi-temporal comparisons complicated or even impossible (Seebach, Strobl, San Miguel-Ayanz, Gallego, & Bastrup-Birk, 2011). The lack of accessibility to national forest data poses another complication because many countries in Eastern Europe treat forest maps and precise forest statistics as either commercially sensitive or even a matter of national security, and thus prohibit its distribution beyond governmental agencies. Even where forest inventory information is in principle available, it is often hard to obtain from national (or sometimes regional) agencies where it is stored in a variety of formats.

Remote sensing (RS) data can provide an alternative data source to quantify forest cover and change independent of official governmental data sources. Information derived from satellite imagery, however, is not equivalent to inventory data collected by forest managers. Optical remote sensing data is suitable for mapping land-cover (tree canopy cover, dominant tree species composition) while national forest inventory data focuses on land-use (e.g., forest land). This means that while tree canopy cover change can be readily observed with remote sensing data, it is not directly comparable to harvested timber volumes reported by the national forest statistics. As a result, remote sensing data are rarely used as a primary source for national forest inventories, and statistical reports due to differences between land-use and land-cover forest definitions (Tomppo et al., 2010). The recent expansion in remote sensing-based forest monitoring products, however, highlights that these data could be valuable for many applications. First, remote sensing-based products can cover vast areas consistently, avoiding discontinuities due to administrative and national boundaries (Hansen et al., 2013; Kuemmerle, Radeloff, Perzanowski, & Hostert, 2006; Pekkarinen, Reithmaier, & Strobl, 2009; Potapov, Turubanova, & Hansen, 2011). Second, long-term records of satellite observations now available in image archives allow forest change quantification over several decades (Baumann et al., 2012; Griffiths, Muller, Kuemmerle, & Hostert, 2013; Margono et al., 2012; Potapov et al., 2012).

Spatial and temporal consistency is an inherent property of remote sensing-based forest cover and change products, alleviating the need for harmonization procedures commonly applied to regional and national forestry inventory data (Seebach et al., 2011; Tomppo et al., 2010). Simple biophysical criteria such as forest cover (defined using certain tree canopy cover thresholds without attribution to specific land cover categories and land use) make remote sensing-based products more suitable to assess carbon change than national forest inventories that are based on land use definitions (DeFries et al., 2002; Harris et al., 2012; Tyukavina et al., 2013). At the same time, remote sensing-based forest cover change analysis requires less effort and time than ground surveys, and can be performed in areas of limited ground access. This is why remote sensing-based products are widely used for multi-national forest assessments and change estimations, and their results serve as a baseline for carbon modeling and socio-economic analyses as well as for studies of landscape dynamics and biodiversity patterns (Burgess, Hansen, Olken, Potapov, & Sieber, 2012; Griffiths et al., 2012; Hansen et al., 2013; Harris et al., 2012; Kuemmerle, Hostert, Radeloff, Perzanowski, & Kruhlov, 2007; Tyukavina et al., 2013; Wendland et al., 2011).

While there have been prior assessments of forests in Europe with remote sensing (e.g., Gallaun et al., 2010; Pekkarinen et al., 2009; Schuck et al., 2003), none of them analyzed the full Landsat record for all of Eastern Europe. The lack of a comprehensive analysis of forest dynamics in Eastern Europe is unfortunate, because the region has witnessed numerous changes in forest cover since the collapse of socialism. Several remote sensing-based forest cover change projects have documented some of these changes (Baumann et al., 2012; European Environment Agency, 2007; Griffiths et al., 2013; Kuemmerle et al., 2009; Pekkarinen et al., 2009; Potapov et al., 2011). However, prior projects have several limitations precluding their use for analyses of forests dynamics across Eastern Europe: (i) none of these products cover the entire region; (ii) the methodologies used in different studies are not compatible; (iii) validation results are inconsistent and hard to compare; and (iv) with few exceptions (Potapov et al., 2011), products are not readily available.

Our research goal here was to fill these gaps and to produce a forest cover change product for all of Eastern Europe for nearly three decades using a consistent set of remote sensing data, methodology, and definitions. Our first objective was to develop a methodology that would allow multi-sensor data integration and seamless forest cover and change mapping. The methodology that we developed was then implemented to map forest cover change in Eastern Europe from 1985 to 2012. Our second objective was to provide consistent and rigorous validation of the reported forest cover change. Lastly, our third objective was the unrestricted sharing of the resulting product for further analyses (http://glad.geog.umd.edu/europe/). While we provide here an overview of the results and discuss potential forest change factors, the in-depth analysis of social and economic drivers of the observed forest changes was outside the scope of this project.

2. Data and methods

2.1. Study area

Our study area included the Eastern European countries that formed the "Eastern Bloc" until the end of the 1980s, except the former German Democratic Republic (aka East Germany, now part of Germany), and Albania (which disassociated from the Eastern Bloc in 1961). The study area included several former USSR republics (Estonia, Latvia, Lithuania, Belarus, and Ukraine) and the European part of Russia (Fig. 3A). The 2012 national and administrative boundaries of the countries were obtained from the Global Administrative Areas Dataset (GADM v2.0, http://www.gadm.org/). Because of the large variability in the hierarchy of administrative units as well as their size among the countries in our study area, we performed the sub-national analysis for administrative units only for the largest countries (Russia, Ukraine, Belarus, and Poland). For Romania and Bulgaria, we used the Eurostat territorial units for statistics (NUTS level 2, GISCO — Eurostat, European Commission; http://epp.eurostat.ec.europa.eu/) and the other countries were analyzed at the national level. To simplify area estimation, all data was processed in the Albers Equal Area projection with a spatial resolution of 30 m per pixel. The total study area encompassed 600 million ha, or 6.7 billion pixels.

2.2. Landsat imagery process

We analyzed Landsat Thematic Mapper and Enhanced Thematic Mapper Plus (TM/ETM+) imagery from the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Data Center data archive. All imagery available in the USGS archives as off November 2013 were used for our project. In total, we processed 59,539 Landsat images, including 3436 from Landsat 4 TM, 26,400 from Landsat 5 TM, and 29,703 from Landsat 7 ETM+. The selected imagery dataset included all Level 1 Terrain corrected (L1T) growing season images from 1984 until the end of 2012 for the 527 Worldwide Reference System 2 (WRS-2) Path/Row scenes in our study area. We defined start and end of the growing season using Moderate Resolution Imaging Spectroradiometer (MODIS)-based 16-day Normalized Difference Vegetation Index (NDVI) profiles derived within MODIS-based forest cover mask for each Landsat footprint (Potapov et al., 2011). Consistent with our earlier research (Potapov et al., 2011), the growing season was defined as the sum of all 16-day intervals having an NDVI equal to or above 90% of the maximum annual NDVI.

All reflective bands (excluding ETM+ panchromatic band) of each Landsat image were converted to Top of Atmosphere (TOA) reflectance and the thermal band (high gain thermal band for ETM+) was converted to brightness temperature (Chander, Markham, & Helder, 2009). We did not conduct an atmospheric correction. A set of Quality Assessment (QA)

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