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Using the Landsat record to detect forest-cover changes during and after the collapse of the Soviet Union in the temperate zone of European Russia

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ABSTRACT

The political breakdown of the Soviet Union in 1991 provides a rare case of drastic changes in social and economic conditions, and as such a great opportunity to investigate the impacts of socioeconomic changes on the rates and patterns of forest harvest and regrowth. Our goal was to characterize forest-cover changes in the temperate zone of European Russia between 1985 and 2010 in 5-year increments using a stratified random sample of 12 Landsat footprints. We used Support Vector Machines and post-classification comparison to monitor forest area, disturbance and reforestation. Where image availability was sub-optimal, we tested whether winter images help to improve classification accuracy. Our approach yielded accurate mono-temporal maps (on average >95% overall accuracy), and change maps (on average 93.5%). The additional use of winter imagery improved classification accuracy by about 2%. Our results suggest that Russia's temperate forests underwent substantial changes during the observed period. Overall, forested areas increased by 4.5%, but the changes in forested area varied over time: a decline in forest area between 1990 and 1995 (−1%) was followed by an increase in overall forest area in recent years (+1.4%, 2005–2010), possibly caused in part by forest regrowth on abandoned farmlands. Disturbances varied greatly among administrative regions, suggesting that differences in socioeconomic conditions strongly influence disturbance rates. While portions of Russia's temperate forests experienced high disturbance rates, overall forest area is expanding. Our use of a stratified random sample of Landsat footprints, and of summer and winter images, allowed us to characterize forest dynamics across a large region over a long time period, emphasizing the value of winter imagery in the free Landsat archives, especially for study areas where data availability is limited.

1. Introduction

Land-cover and land-use-change (LCLUC) is one of the most important components of global environmental change (Foley et al., 2005). Among the different land cover classes, changes in forests are particularly important because of their ability to sequester atmospheric carbon sequestration and their potential to help mitigating climate change (Bonan, 2008; FAO, 2010). Remote sensing has played a key role in monitoring forest change at multiple scales and in different regions of the world (Hansen et al., 2008; Kennedy et al., 2011; Potapov et al., 2011).

LCLUC is often linked to socio-economic changes, leading to conceptual models that describe LCLUC as a function of a country's economic development (e.g., Foley et al., 2005; Lambin et al., 2003). However, these conceptual models usually assume relatively continuous development of political and economic conditions, and it is less clear how drastic and rapid changes in political and economic decisions affect land use. A prime example of a drastic change is the collapse of the Soviet Union in 1991. The switch from a state-controlled economy towards an open market system, and the institutional transformation in Russia resulted in major changes in forest legislation, and the privatization of both the timber industry (Turnock, 1998; Wendland et al., 2011) and the agricultural sector, which had substantial influences on agricultural intensity (Lerman, 2009; Prishchepov et al., in review).

Forest cover changed markedly in many parts of Eastern Europe after the collapse of the Soviet Union, and remote sensing has played a key role in mapping these changes. For example, analyses of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data in the Carpathians revealed that the transition period after the breakdown of the Soviet Union was partially characterized by widespread forest harvests (Griffiths et al., 2012; Knorn et al., 2012; Main-Knorn et al., 2009), including illegal logging (Kuemmerle et al., 2009). In European

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Russia's boreal forest, harvesting rates were about 1.5% between 2000 and 2005 according to a wall-to-wall analysis of Landsat data (Potapov et al., 2011). In addition to Landsat based studies, European Russia was also part of studies that investigated global forest-cover changes using the Moderate Resolution Imaging Spectroradiometer (MODIS) (Hansen et al., 2010; Potapov et al., 2008). However, past studies either focused on a large area over a short and recent time period, or they analyzed long-term change, but were geographically limited to a smaller study area. What is lacking is a study of the temperate forests of European Russia that analyzes a long time series in the entire region.

One reason that such a study has not been undertaken previously is the quality and volume of data that is needed, in both the spatial and temporal domain. While MODIS imagery provides very frequent information for large areas, these observations are made at moderate spatial resolution (250 to 500 m), which limits their utility for small scale landscape changes. Moreover, since MODIS only started recording the Earth's surface in 2000, the timeframe of available data is too short to analyze forest-cover changes during the last years of socialism and the early post-socialist period. On the other hand, Landsat sensors (especially TM and ETM+) provide high-resolution data (30 m) that are available continuously from 1984 to the present, which makes them ideal for addressing questions of post-Socialist forest-cover change. However, Landsat sensors' relatively narrow swath width (approximately 185 km) makes Landsat data more challenging to use wall-to-wall across large areas. The lower temporal repeat cycle (16 days, 8 days when considering the overlap areas to neighboring footprints in higher latitudes) as one consequence of the narrow swath width and frequent obstructions by clouds lead in some regions of the world to a maximum of 1–2 suitable images per growing season at best, making wall-to-wall-coverage across large areas impossible. An alternative approach for describing forest dynamics across a larger region is to statistically sample a subset of Landsat footprints, greatly reducing the amount of data needed. Such an approach has been used for the United States as part of the North American Forest Dynamics (NAFD) project (Goward et al., 2008) in which 23 footprints were selected and analyzed using Landsat Time Series Stacks (LTSS; Huang et al., 2009a). Similarly, agricultural expansion on expense of intact forests has been investigated in the tropics (Gibbs et al., 2010). Achard et al. (2002) studied the world's humid tropical forests in the TREES-2 project using a sample of overall 100 Landsat scenes (quarters and full scenes). These scenes were selected using a deforestation risk map, which had been created previously based on expert knowledge, and considered higher sampling probabilities in deforestation hot spot areas. The FAO Forest Resources Assessment 1990 used a stratified sample of 117 Landsat TM scenes in the tropics containing at least 10,000 km^2 land surface (FAO, 1996) to assess forest cover. For an analysis of the European Union using a sample of Landsat TM scenes, Gallego (2005) selected his sample based on Thiessen polygons and a stratification process. Stehman (2005) generally showed that focusing on a sample rather than on the entire population yields better estimates, when the improvement of error during the analysis of the sample outweighs the introduction of the sampling error. As such, in the present study, we focused on a sample of Landsat footprints rather than on a wall-to-wall coverage.

Our study also focuses on capturing local and regional forest-cover changes which, we assume, vary across the entire region. Caused by the low data availability that did not allow us to cover the region wall-to-wall for our entire time period of interest, we used a stratified random sample and selected 12 Landsat footprints across the temperate zone of European Russia.

While the use of a statistical sample reduces the number of footprints necessary to study, it does not completely eliminate the problem that cloud-free imagery during the growing season is often limited. Leaf-off imagery in spring and fall can result in classification errors between deciduous trees and non-forested vegetation classes (Reese et al., 2002). We hypothesized that the additional use of a winter image can help overcome this issue, especially for the accurate delineation of forest boundaries. Landsat imagery from the winter season can be useful because of the strong radiance contrast in these areas during the winter (Liira et al., 2006; Peterson et al., 2004). Grasslands and open spaces are completely covered with snow during the winter, leading to high visible reflectance while deciduous and needle leaf forests have a lower reflectance due to branches and shadows. In other words, adding a second image from the winter period of the same year may possibly increase the overall accuracy of the classification by helping to distinguish grass areas from deciduous forests. The use of winter imagery has been successfully shown in the past: their addidional use led to an accuracy of 89% for quantification of bamboo understory growth in a mixed forest area (Wang et al., 2009). Winter imagery use was also reported providing an alternative to hyperspectral data for mapping forest wildlife habitat in the central and southern Appalachians (Tirpak & Giuliano, 2010). In the most recent study, Stueve et al. (2011) tested snow-covered Landsat imagery in North America and found that they reduce commission errors of disturbance areas by nearly 28%. Based on these prior findings, we decided to investigate if winter imagery can also improve forest/non-forest-classifications in the temperate region of Russia.

Another shortcoming of most prior studies in European Russia is that they examined only permanent forests and forest disturbances, while ignoring forest recovery (defined here as forest regeneration on disturbance sites, as well as forest expansion onto land that was not forested at the beginning of the Landsat record). Rates of forest recovery are of paramount importance for studies of carbon sequestration both above ground (Böttcher et al., 2008; Houghton, 2005) and in the soil (Guo & Gifford, 2002). Forest recovery is particularly important in the former Soviet Union and Eastern Europe (Vuichard et al., 2008). For example, widespread farmland abandonment (as documented by Baumann et al., 2011; Kuemmerle et al., 2008; Prishchepov et al., in review) suggests that large areas of former farmland are reverting to forests, which creates a large carbon storage potential (Kuemmerle et al., 2011; Olofsson et al., 2011). However, the extent and the intensity of forest recovery in the temperate zone of European Russia are not well known.

The overarching goal of our study was therefore to characterize regional differences of post-socialist forest-cover changes in the temperate region of European Russia using a representative sample of Landsat footprints. More specifically, our objectives were to:

- quantify the changes in forested areas in 5-year-increments from 1985 to 2010 across a stratified random sample of 12 Landsat footprints,
- determine forest recovery rates in these footprints before and after the collapse of the Soviet Union and compare these patterns with those in other eastern European countries, and
- test whether the inclusion of a winter image increases classification accuracy.

2. Study area

Our study region included three Russian federal districts, 27 federal districts (hereafter: ‘regions’), which are subdivided into 821 municipal districts (Fig. 1). The two largest cities of European Russia, St. Petersburg and Moscow, were located in our study region. Russia contains 20% of the world's forests (about 809 million ha; FAO, 2010), and in the temperate region, temperate coniferous, broadleaf, and mixed forests dominate the landscape.

European Russia's forest sector and forest legislation underwent several substantial changes since 1991, including privatization of the timber industry, and changing decentralizations and re-centralizations of the forest administration between federal, local and regional administrators (Eikeland et al., 2004; Wendland et al., 2011). Based on the 1993 *Principles of Forest Legislation*, forest management and