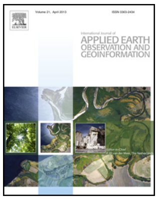
International Journal of Applied Earth Observation and Geoinformation 35 (2015) 320–328

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag



The effect of atmospheric and topographic correction on pixel-based image composites: Improved forest cover detection in mountain environments

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ARTICLE INFO

Article history:
Received 9 June 2014
Accepted 9 October 2014
Available online 23 October 2014

Keywords:
Forest cover mapping
Classification accuracy assessment
Topographic correction
Landsat
Pixel-based compositing
Mountain areas

ABSTRACT

Quantification of forest cover is essential as a tool to stimulate forest management and conservation. Image compositing techniques that sample the most suited pixel from multi-temporal image acquisitions, provide an important tool for forest cover detection as they provide alternatives for missing data due to cloud cover and data discontinuities. At present, however, it is not clear to which extent forest cover detection based on compositing can be improved if the source imagery is firstly corrected for topographic distortions on a pixel-basis. In this study, the results of a pixel compositing algorithm with and without preprocessing topographic correction are compared for a study area covering 9 Landsat footprints in the Romanian Carpathians based on two different classifiers: Maximum Likelihood (ML) and Support Vector Machine (SVM). Results show that classifier selection has a stronger impact on the classification accuracy than topographic correction. Finally, application of the optimal method (SVM classifier with topographic correction) on the Romanian Carpathian Ecoregion between 1985, 1995 and 2010 shows a steady greening due to more afforestation than deforestation.

Introduction

The Millennium Development Goals Report (2013) stated that accelerated progress and actions are needed for forest conservation. Forest cover changes affect crucial ecosystem services, such as water supply, biodiversity, carbon storage, and climate regulation (Foley et al., 2005). Assessing the rate and spatial pattern of forest cover change is challenging since large forests are present in rather inaccessible and rough mountain areas (Lambin and Geist, 2006). Multiple efforts have been made to quantify global forest cover changes and forest transitions (Hansen and DeFries, 2004; Meyfroidt and Lambin, 2011; FAO, 2012). These global inventories were either sample-based or based on coarse spatial resolution data (Hansen et al., 2013). Moreover, time-series analysis of forest cover change based on high resolution satellite data have been performed in different countries, e.g. Indonesia (Broich et al., 2011), United States of America (Kennedy et al., 2010; Hansen et al., 2011), Democratic Republic of Congo (Potapov et al., 2012), and Romania (Griffiths et al., 2013b). In contrast, Hansen et al. (2013) presented a global forest cover change inventory based on high resolution satellite data. Remote sensing techniques are privileged monitoring tools and yet suffer from methodological challenges that need to be resolved by correction methods (Lhermitte et al., 2011a; Balthazar et al., 2012).

The opening of the Landsat archive provides opportunities to reconstruct forest cover changes for large areas on a 30–60 m spatial scale (Loveland and Dwyer, 2012; Giri et al., 2013; Hansen et al., 2013). The use of the Landsat archive with 185 km × 185 km footprint size and a 16-day repeat cycle, however, poses several challenges, ranging from image mosaicking over large areas that cover more than one footprint, to optimal data selection due to cloud cover (Ju and Roy, 2008; Lhermitte et al., 2011b; Griffiths et al., 2013a) and data discontinuities due to sensor or data related errors (e.g. the failure of scan line correction in Landsat 7; Arvidson et al., 2006). Moreover, optimal processing is essential to obtain consistent reflectance values for each Landsat image, where processing methods range from cloud/shadow/water screening and quality assessment, and image normalization for atmospheric conditions and surface anisotropy (Potapov et al., 2011, 2012; Hansen et al., 2013) to physically based atmospheric and topographic correction methods (Minnaert, 1941; Teillet et al., 1982; Berk et al., 1998; Meyer et al., 1993; Jensen, 1996; Richter, 1996; Vermote et al., 1997; Veraverbeke et al., 2010). More recent, comparisons in the performance of different combinations of atmospheric and

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http://dx.doi.org/10.1016/j.jag.2014.10.006
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topographic corrections have been made (Riano et al., 2003; Vincini and Frazzi, 2003; Vicente-Serrano et al., 2008; Gao and Zhang, 2009; Vanonckelen et al., 2013, 2014). Finally, the processed Landsat images can be used to detect changes on the original Landsat footprints or on composites derived from the Landsat data, where the latter data have the advantage that they (i) allow solutions over large areas for missing data due to cloud cover and data discontinuities, (ii) avoid artificial partitioning into footprint, (iii) increase observation frequency by across track overlap exploitation (Masek et al., 2006).

Pixel-based image compositing (PBIC), which was initially developed for wide-swath sensor data with clouds (Holben, 1986; Cihlar et al., 1994), selects the most suitable pixel or set of pixel values for each location from a series of available source images. Initial PBIC methods aimed at developing cloud-free composites and implemented the parameter 'distance from cloud' as a criterion (Hansen et al., 2008; Roy et al., 2010). Other PBIC methods were developed for the removal of the missing lines in Landsat-7 imagery (Goward et al., 1999; Arvidson et al., 2001, 2006). In 2010, Kennedy et al. presented the Landsat-based detection of trends in disturbance and recovery (LandTrendr) approach which implements change detection algorithms to perform temporal segmentation and fitting of Landsat time series. Griffiths et al. (2013a) presented a large scale forest cover change mapping across the entire Carpathians between 2000 and 2010. The most recent worldwide forest inventory was performed between 2000 and 2012 by Hansen et al. (2013) and used per-pixel set of cloud-free Landsat observations that was normalized for atmospheric conditions and surface anisotropy but not physically corrected for atmospheric or topographic effects. Pixel-based image compositing clearly offers new possibilities for large scale analysis of land and forest cover dynamics. The homogeneous image composites can be classified and analyzed in a single operation resulting in consistent forest cover (change) maps. In general, the impact of a topographic preprocessing method on the results of a PBIC has not been studied. At present, it is unknown to what extent the results of PBIC can be improved if topographic preprocessing is applied on the source images.

Therefore, in this study a pixel-based topographic correction is integrated in the compositing algorithm of Griffiths et al. (2013a) with the objective to (i) assess the impact of topographic correction on classification accuracy of PBICs, and (ii) compare the effect of topographic correction with different classifiers. Within this framework, a large area mapping was performed on the Romanian Carpathian mountains.

Materials and methods

Study area

The study area consist of nine Landsat footprints (±107,000 km^2) in the Romanian part of the Carpathian Ecoregion, which constitutes more than half of the total Carpathian region (Fig. 1) and contains about 60% of the Carpathian forest cover (Webster et al., 2001). The study area is characterized by mountainous terrain with elevations up to 2544 m and a temperate-continental climate. The growing season is between April and October, and varies in response to annual rainfall and elevation (Rotzer and Chmielewski, 2001). Both temperature and precipitation are highly inversely correlated with elevation. This mountain area is characterized by a mean annual temperature of ±7 °C and a mean annual rainfall ranging between 750 and 1400 mm (Mihai et al., 2007; Müller et al., 2009). Warm summers alternate with cold winters and high precipitation rates, mostly as snow. In summer, showers and thunderstorms occur frequently, reaching peak intensity in June (Mihai et al., 2007). The bedrock in this area consists of crystalline schist, sedimentary rock deposits as limestone and volcanic layers (Griffiths et al., 2013a). Major soils include *Podzols* in the mountain zone and *Cambisols* in the foothill zone (FAO/UNESCO/WRB, 1998).

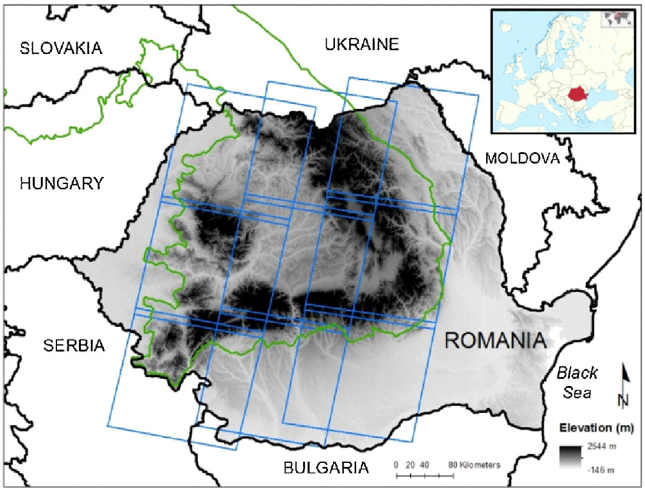

Fig. 1. Location of Romania in eastern Europe and indication of the Carpathian Ecoregion (irregular polygon) and the nine Landsat footprints comprising the Romanian Carpathian Ecoregion (rectangles). Romania was overlaid with the Shuttle Radar Topography Mission elevation data.

Data and methodology

Satellite and elevation data

Landsat imagery was selected from the Landsat archive based on two criteria. First, all available Landsat TM and ETM+ images from the USGS Landsat archive with a precision terrain correction L1T and covered by less than 70% clouds were considered (Griffiths et al., 2013a). Secondly, all images acquired within a two year range of the target years 1985, 1995 and 2010, and between mid-February and mid-November were retained. This range of acquisition months was included to avoid low sun elevation angles, shadowing and high snow coverage, but also allowed to maximize the amount of pixels in the final composite. The disadvantage of this large range of months (e.g., different phonological stages) was moreover minimized by inclusion of the day of year (DOY) in a parametric weighting scheme (see subsection "Pixel-based image compositing").

Topographic correction was performed based on the co-registered 3 arc sec (90 m × 90 m) digital elevation model (DEM). This space shuttle radar topography mission data (SRTM version 4.1; Slater et al., 2006) from CGIARCSI/NASA, which was resampled to the 30 m × 30 m Landsat dataset by means of a bicubic spline interpolation. Although the resampled SRTM data do not allow an perfect topographic correction (e.g., Zhang et al. (2015) concluded that a 30 m DEM achieved the required topographic correction accuracy for 90–500 m resolution remote sensing images), it is the best DEM available and it was preferred over the 1 arc sec (30 m × 30 m) ASTER GDEM data as several studies indicate that the ASTER GDEM is more subject to artifacts such as stripes or cloud anomalies (Van Ede, 2004; Hirt et al., 2010).

Pixel-based image compositing

Griffiths et al. (2013b) implemented a PBIC algorithm to produce cloud-free and best observation composites of leaf-on phenology for a target year. Suitability of a given pixel was based on a parametric decision function which included: (1) the difference between acquisition year and target year, (2) the acquisition DOY, and (3)