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Red-edge vegetation indices for detecting and assessing disturbances in Norway spruce dominated mountain forests

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ABSTRACT

Here we propose an approach to enhance the detection and assessment of forest disturbances in mountain areas based on red-edge reflectance. The research addresses the need for improved monitoring of areas included in the European Natura 2000 network. Thirty-eight vegetation indices (VI) are assessed for sensitivity to topographic variations. A separability analysis is performed for the resulting set of ten VI whereby two VI (PSSRc2, SR 800/550) are found most suitable for threshold-based OBIA classification. With a correlation analysis (SRCC) between VI and the training samples we identify Datt4 as suitable to represent the magnitude of forest disturbance. The provided information layers illustrate two combined phenomena that were derived by (1) an OBIA delineation and (2) continuous representation of the magnitude of forest disturbance. The satisfactory accuracy assessment results confirm that the approach is useful for operational tasks in the long-term monitoring of Norway spruce dominated forests in mountainous areas, with regard to forest disturbance.

Introduction

Forest ecosystems cover significant areas of mountainous regions all over the world. Their importance and the need for further improvements in detailed monitoring over large spatial extents have been stated in Price et al. (2011). This is also reflected in the Natura 2000 management requirements for monitoring and reporting on the conservation status of habitats (e.g. code 91XX, 94XX), stipulated in Article 17 of the European Union Habitats Directive (HabDir, Council Directive 92/43/EEC, European Commission, 2006). Habitat mapping and monitoring of Natura 2000 sites by Earth observation (EO) offers several advantages over traditional field mapping programmes including, for example, more rapid map generation, valuable insights into remote and inaccessible terrain, and greater repeatability of the analyses (Vanden Borre et al., 2011).

The presence of deadwood is increasingly recognized as being an important structural component of well-functioning natural forest ecosystems and acts as a critical indicator for habitat provision (e.g. Radu, 2007). Forest disturbance maps highlighting the locations and spatial distributions of deadwood within a forest can assist in fulfilling the management and nature conservation objectives of the Natura 2000 network. Different terminologies exist with respect to deadwood and specific sub-categories (e.g. Schuck et al., 2004; Rondeux and Sanchez, 2009). In our research forest disturbance is assumed to mainly originate from natural disturbances caused by abiotic factors such as windstorms, or by biotic factors such as insect pests (mostly infestations of the spruce bark beetle, *Ips typographus* [L.]). The forest disturbance categories used in this context comprise standing or lying deadwood, and standing trees in different (but continuous) stages of defoliation and discolouration (specified in the Commission Regulation (EEC) No. 926/93).

Mapping forest disturbances commonly yields (1) information on deforestation and reforestation (e.g. Masek et al., 2008), and (2) an overview of forest conditions through assessments of the magnitude of disturbance (e.g. Meigs et al., 2011). Monitoring of forests over large spatial extents has been performed with medium to low resolution images, using per pixel approaches (e.g. Cohen and Goward, 2004). Our research utilizes data capable to meet reporting obligations on both local and regional scales. The analysis of (V)HR (very high resolution) imagery, in combination with an object-based image analysis (OBIA) approach (e.g. Lang, 2008), offers a more appropriate way to meet the detailed requirements for the Natura 2000 network (Nagendra et al., 2013).

New opportunities for vegetation assessment including the availability of extended spectral ranges such as the red-edge band emerged with the launch of RapidEye and WorldView-2 satellites. The use of the red-edge band proved to be more effective

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(e.g. Schuster et al., 2012) than the 'traditional' ones (e.g. contrast between NIR and red, or SWIR). The use of red-edge reflectance has the advantage of producing a greater sensitivity to more levels of chlorophyll *a* and *b* and to variations in chlorophyll content, and has been shown in experimental studies to be effective for assessing vegetation stress (e.g. Datt, 1998; Le Maire et al., 2004).

The overall aim of this research is to evaluate the effectiveness of vegetation indices (VI) including the red-edge band and other commonly used VI for detecting and assessing of forest disturbances in mountainous areas. The most suitable VI are selected to develop an EO-based approach for improved detection. Furthermore, two phenomena are combined in an information layer to illustrate the (1) discrete classification derived by OBIA and (2) the continuous representation of the magnitude of forest disturbance. The objective is to provide an approach that can be adapted to different spruce-dominated forest areas using data of different resolutions.

Methods

Study sites and data

We chose the two study sites Kalkalpen National Park ('KANP') with a subset of 88 km^2 and the Bohemian Forest ('BF') with a subset of 207 km^2 in size, that both represent spruce-dominated forests in mountainous areas (Fig. 1). The KANP is located in the alpine biogeographical region and is part of Austria's largest non-fragmented forest area. The BF is situated in the continental bio-geographical zone and forms one of the largest forest complexes in Central Europe, comprising the Bavarian Forest National Park in Germany and the Šumava National Park in Czech Republic. The altitudes of both study areas range between 385 and 1963 m in KANP, and 700–1456 m in BF. The dominating habitat types are summarized under the Codes 91XX *Forests of Temperate Europe* and 94XX *Temperate mountainous coniferous forests* (Annex I, HabDir).

The study areas are included in the European Natura 2000 network of protected sites (codes: AT3111000 and DE6946301 [Birds Directive and HabDir], CZ0314024 [HabDir]) and are among pilot sites to show the potential of EO for the detection of forest disturbance.

Due to long-term forest management the tree species composition, in both study sites, in particular in the mixed mountain forests, has changed to a higher percentage of Norway spruce (*Picea abies* (L.) H. Karst). Now these forests are characterized by low tree species diversity and an increased sensitivity to changing mountain climate conditions and insect infestations. In the past the forest stands in both national parks have faced severe attacks from spruce bark beetles, which followed large scale windthrows caused by major storm events. It has to be mentioned that in these more or less even-aged spruce-dominated forests the spread of the spruce bark beetles were favoured. In the 1950ies, management measures were enforced for returning the forests to natural habitats, allowing a transition to the characteristic species composition due to the specific site conditions in these mountainous regions, i.e. a mixture of beech (*Fagus sylvatica* L.), spruce, and European silver fir (*Abies alba Mill)*. Furthermore these management measures contribute to the conservation of the habitat type *Luzulo-Fagetum beech forests* (habitat code: 9110), which has been assessed to *unfavourable inadequate* to *bad* (EEA, 2009) habitat conditions in these regions.

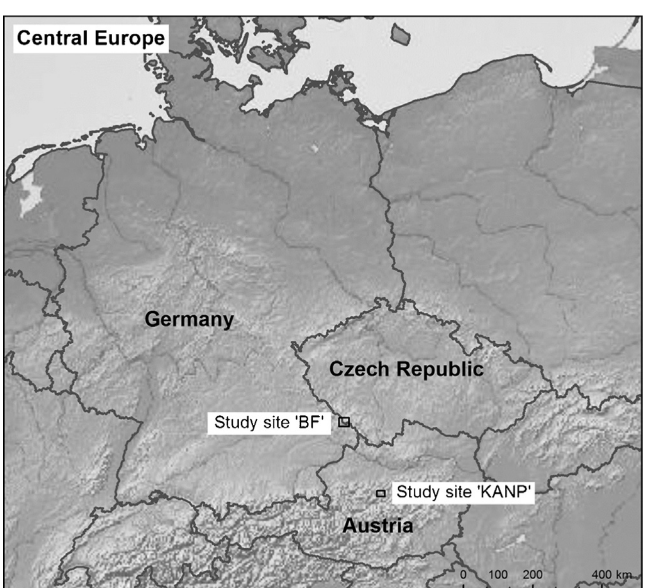

Fig. 1. Locations of study sites KANP and BF.

The research was carried out using data from two (V)HR satellite sensors equipped with a red-edge band. The RapidEye (BlackBridge) data yields multispectral imagery with a spatial resolution of 5 m in five optical bands (440–850 nm). Archived, radiometrically and geometrically corrected images without atmospherically calibration were used for the two test sites. Image acquisition date for KANP was 11 September 2011 and for BF 22 June 2011. In addition, WorldView-2 image (Digital Globe) was used for the KANP area, for testing and transfer purposes. This image was also radiometrically and geometrically corrected without atmospherically calibration and was acquired on the same day as the RapidEye data for this area. The WorldView-2 sensor provides data with a spatial resolution of 2 m (pan-sharpening was not applied), which includes eight multispectral bands (400–1040 nm).

Sample collection strategy

Sample areas representing different forest disturbance stages were identified by independent interpretation of RapidEye images, with the participation of field specialists and making use of field data across the study areas. Since the availability of field data was limited due to the mountainous character of the study area, EO-based analysis was performed to detect fine-scaled forest disturbance areas. The workflow of field sampling and sample processing is presented in Fig. 2.

The classification scheme to assess forest disturbance follows the requirements of the Commission Regulation (EEC) No. 926/93 (CEC, 1993) for periodic inventories of forest disturbance. The scheme used in our research was modified to make it more general due to the limitations of EO methods for detecting detailed forest characteristics, compared to field inventories (Table 1).

Vegetation indices performance evaluation

Thirty-eight VI (Supplement 1) reflecting chlorophyll activities were chosen from those recommended for vegetation analysis by the Index Database (Henrich et al., 2012). We selected a set of VI applicable for both sensors, RapidEye and WorldView-2.

Sensitivity to topographic variations

First we assessed VI sensitivity to topographic variations: slope and aspect (Fig. 2/Step2A). These parameters are one of the most critical when mountainous areas are analyzed (Richter and Schlapfer, 2002). Following the approach of Matsushita et al. (2007) the VI values were compared using the same number of sample points (Fig. 2/Step1A) located at all combinations of slope and aspect presented within the study area, derived from a 10 m resolution digital elevation model. The analysis was performed per class c0, c3, c4 for comparability of VI behaviour. The influence of the