Remote Sensing of Environment 140 (2014) 533–548

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Assessing the potential of hyperspectral imagery to map bark beetle-induced tree mortality

Fabian Ewald Fassnacht [a,*], Hooman Latifi [b], Aniruddha Ghosh [c], Pawan Kumar Joshi [c], Barbara Koch [a]

[a] Chair of Remote Sensing and Landscape Information Systems (FELIS), University of Freiburg, Tennenbacherstraße 4, 79106 Freiburg, Germany
[b] Department of Remote Sensing in cooperation with German Aerospace Center (DLR), Institute of Geography and Geology, University of Wuerzburg, Oswald-Kuelpe-Weg 86, 97074 Wuerzburg, Germany
[c] Department of Natural Resources, TERI University, New Delhi, India

ARTICLE INFO

Article history:
Received 6 March 2013
Received in revised form 12 August 2013
Accepted 12 September 2013
Available online 18 October 2013

Keywords:
Hyperspectral remote sensing
Genetic algorithm
Bark beetle infestation
SVM classification
Feature selection
Tree mortality mapping

ABSTRACT

Natural hazards caused by insect outbreaks, such as those induced by the European bark beetle (*Ips typographus* L.), are among the most extensive disturbances affecting forest health in various geographical regions. Accurate and up-to-date knowledge of the spatial distribution of bark beetle-infested trees is critical for forest managers to effectively plan appropriate countermeasures and predict future bark beetle infestation dynamics. In this study, three scenarios for mapping bark beetle-induced tree mortality based on airborne hyperspectral data (HyMap) were examined including combining a genetic algorithm (GA) for feature selection with a supervised support vector machine (SVM) classification. The scenarios differed in how the mortality classes (used to extract the spectral signatures) were defined. Scenario 1 included three mortality classes, while Scenario 2 and 3 each included only one general mortality-related class but with different definitions. The classes, derived from the three scenarios, served as inputs into feature selection facilitated by the GA. The most stable bands, selected by the GA, were then used as input bands for a bootstrapped supervised SVM classification procedure. In two of the three scenarios, the trained classifier was additionally applied to a second independent hyperspectral image to evaluate the stability of the spectral signatures derived from the training samples. The classification procedure was further refined by varying the number of input bands and the input data types, where the bands not only included the original reflectances of the HyMap images but also a first order Savitzky–Golay derivation and continuum-removed spectra. The results of the study indicate that an accurate differentiation of three mortality classes was not possible with the applied methodology. The defined pre-visual “green mortality stage” class in particular was found to be heavily overestimated based on the qualitative analysis of the classified maps and validation statistics (error of commission 65% as shown by the user's accuracy).

However, on the other hand, the mapping of dead trees was possible with notably high overall accuracies (OAs) (84%–96%). These results could also be transferred to the second independent hyperspectral image, in which the separation between the healthy trees and the dead trees was possible with OAs of 94%–97%. Somewhat lower but still reasonable OAs (76%–85%) were found when all defined classes were considered. The main confusion occurred between dead trees and sparsely vegetated soil.

GA analysis showed that bands that notably contributed to high classification accuracies were frequently located in the visual part of the spectrum, close to the green peak (560 nm), as well as around the chlorophyll absorption feature (680 nm) and the red edge rise (690 nm). In some of the tested cases, additional bands in the SWIR (1532 nm) and one in the NIR (1076 nm) were stably selected by the GA, which indicated the importance of these bands in the classification process.

1. Introduction

Insect infestations have been documented to be a serious threat to the economic and, to a certain extent, the ecological value of the forest ecosystems (Jactel & Vodde, 2011; Niemann & Visintini, 2005). Comparable to non-biotic disturbances such as fires or landslides, insect infestations caused by the European bark beetle (*Ips typographus* L.) or the North American mountain pine beetle (*Dendroctonus ponderosae* Hopkins), for example, are considered to be an inherent part of the natural ecosystem. However, infestations become problematic when they reach epidemic levels, as previously reported for large areas in North America (Wulder, Dymond, White, Leckie, & Carroll, 2006). Research conducted in North America indicates that the expansion of the geographic range of the mountain pine beetle population (due

* Corresponding author. Tel.: +49 761 203 3700, +49 761 203 3694; fax: +49 761 203 3701.
E-mail addresses: fabian.fassnacht@felis.uni-freiburg.de (F.E. Fassnacht), hooman.latifi@uni-wuerzburg.de (H. Latifi), aniru123@gmail.com (A. Ghosh), pkjoshi27@hotmail.com (P.K. Joshi), barbara.koch@felis.uni-freiburg.de (B. Koch).

0034-4257/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.rse.2013.09.014

to favorable climatic conditions) may be correlated with climate change (Carroll, Taylor, Régnière, & Safranyik, 2004; Logan & Powell, 2004; Wulder et al., 2006) as well as with management decisions induced by intensive fire-management activities that may benefit specific tree species (Taylor & Carroll, 2004). In central Europe and Scandinavia, bark beetle infestations, which mainly endanger the Norway spruce (*Picea abies* (L.) Karst), are expected to increase in the near future (Lagergren & Jönsson, 2010). This is particularly troublesome, as the Norway spruce is economically the most important tree species in central and northern Europe. Higher infestation rates are expected due to climatic changes such as more extreme weather events and higher average temperatures that are believed to increase the vulnerability of the Norway spruce. Additionally, bark beetle attacks on the Norway spruce may be more likely under drought conditions (Kazda & Pichler, 1998) or with an increased presence of deadwood in forest gaps (Schroeder, 2010) as a consequence of strong winds (Peltola, Kellomäki, Hassinen, & Granander, 2000). The projected higher average temperatures and prolonged growing seasons can result in a shift from univoltinism to multivoltinism (i.e., from one to two (or more) completely matured bark beetle generations every year (Lange, Økland, & Krokene, 2006; Ogris & Jurc, 2010)) and thereby further increase the pressure on the trees.

For management measures such as clearing wind throws, sanitary logging and pheromone trapping (Kautz, Dworschak, Gruppe, & Schopf, 2011) to be successful, knowledge of the location and intensity of the infestations and the resulting dead trees is of crucial importance. Survey methods for mapping the spatial information on bark beetle infestations extend from local to regional scales. Several Canadian reports (Wulder, Dymond, & Erickson, 2004, 2006, Wulder, Dymond, & White, 2005, Wulder, White, Coops, et al., 2006) provide detailed information on the variety of relevant ground and remote sensing-based survey methods for bark beetle monitoring. These mainly include field campaigns, sketch mapping from helicopters or airplanes and digital remote sensing. Satellite imagery has been used since the early 1990s to map and predict insect infestations (Skakun, Wulder, & Franklin, 2003). Compared to the other described methodologies, digital remote sensing data have the advantage of being compatible with digital forest inventory databases while delivering high positional accuracy. The further benefits of remote sensing combined with automatic processing algorithms lie in the reduction of interpreter bias, which therefore offers greater consistency and reliability among different areas or dates (Wulder et al., 2004).

Studies conducted by Franklin, Wulder, Skakun, and Carroll (2003), Skakun et al. (2003), Wulder, White, Bentz, Alvarez, and Coops (2006) and Meddens, Hicke, Vierling, and Hudak (2013) used Landsat TM and Landsat-7 ETM+ imagery to map trees in the "red stage" of a mountain pine beetle attack. Overall accuracies (OAs) ranging from 67% to 78% have been reported using classification approaches such as stratified maximum likelihood and multi-temporal indices, e.g., enhanced wetness difference index (EWDI) (Skakun et al., 2003). The latter approach was improved by adding spatial information layers and applying logistic regression to indicate the likelihood of trees in the "red stage" of attack rather than using the binary thresholding approach (Wulder, White, Bentz, Alvarez, & Coops, 2006). This improved the classification accuracy of the "red stage" of attack to 86%. Meddens et al. (2013) compared single-date and multi-date approaches based on Landsat imagery. Multi-date approaches using a time series of vegetation indices performed best at intermediate mortality levels (OA of 89.6%), while the single-date approach produced the best results at high mortality levels (OA of 91.0%).

Promising OA results of up to 92% (for trees under medium attack) and 71% (for trees under low attack) were reported when using an unsupervised clustering approach on high resolution IKONOS data (White, Wulder, Brooks, Reich, & Wheate, 2005). White, Wulder, and Grills (2006) reported a producer's accuracy of 71% for separating trees in the "red stage" of attack when applying a logistic regression model on SPOT data at a 10 m spatial resolution. Röder et al. (2009) applied the random forest algorithm for classifying the combination of the red band and the Red-Edge–Green-NDVI of a RapidEye data with the VV polarization of a TerraSAR-X data to map bark beetle-infested spruce trees, reaching an OA of 73.2%.

The enhanced capabilities of hyperspectral data for the detection and mapping of vegetation damage (by using continuous spectral information, spectral derivatives or supporting new narrowband vegetation indices) have been confirmed with studies focusing on field spectrometers (e.g., Carter, 1994; Carter & Knapp, 2001; Cheng, Rivard, Sánchez-Azofeifa, Feng, & Calvo-Polanco, 2010) and airborne (e.g., Coops et al., 2003; Zarco-Tejada, Miller, Mohammed, Noland, & Sampson, 2002) and spaceborne hyperspectral images (White, Coops, Hilker, Wulder, & Carroll, 2007). This last study documented the potential of narrowband indices derived from spaceborne EO1-Hyperion data to estimate the damage levels of forest stands under mountain pine beetle attack. Nevertheless, the operational mapping attempts of the green stage of attack have not yet been successful (Wulder, White, Carroll, & Coops, 2009). Furthermore, accurate mapping of bark beetle-infested trees not only includes the basic challenge of separating dead from living trees but also discriminating among dead trees and other spectrally similar superficies such as sparsely vegetated soil that occurs in forest gaps and clearances. Only a few attempts have dealt with the latter issue (e.g., Meddens, Hicke, & Vierling, 2011).

Summarizing the state-of-the-art utilization of remote sensing data in the context of the detection and mapping of bark beetle infestations clarifies that the potential of airborne and spaceborne hyperspectral data has not yet been sufficiently assessed. The increased spectral resolution of hyperspectral data may be beneficial for the early detection of the stress symptoms of bark beetle-infested trees as well as the improved mapping of tree mortality at a later stage of infestation. Furthermore, only a few studies, which incorporated classification or modeling approaches, also analyzed the portability of the obtained results to other, similar locations. The portability of mapping methods as well as high quality classification maps that are spatially accurate for all relevant classes (not only for the training samples but across the entire region) are major requirements to advance the operational use of remote sensing data for the mapping of bark beetle-induced tree mortality. Based on a review of existing literature, these requisites are not yet fully met. This research aims to assess the potential of hyperspectral data to improve the capabilities to meet the above-mentioned practical requirements.

In pursuit of this aim, airborne HyMap data are employed here to assess their potential to map bark beetle-induced tree mortality by combining a genetic algorithm (GA) for feature selection followed by a supervised support vector machine (SVM) classification. Three classification scenarios (with differing sets of tree mortality classes as well as three different input datasets) were examined. One of the scenarios was based on the detection of three tree mortality stages, whereas the other two focused on accurate mapping of dead trees. To the best of our knowledge, no study has been conducted in central Europe to assess potential improvements in mapping accuracy in a bark beetle scenario when utilizing hyperspectral data in combination with state-of-the-art non-parametric classifiers. By integrating heuristic feature selection, this study also identifies specific spectral regions that are of high importance in detecting and mapping various stages of bark beetle-related tree mortality.

The specific objectives of this study are the following: 1) assess the mapping accuracies of bark beetle-induced tree mortality in three scenarios with differing target classes; 2) identify crucial spectral regions to map bark beetle-induced tree mortality; and 3) propose a classification workflow to map dead trees over multiple images using a commonly-acquired training dataset. Results include recommendations on the optimal type of input data, spectral regions, number of input bands and the definition of considered classes. These objectives specifically address the need for an operational methodology to perform automatic and accurate mapping of bark beetle-induced tree mortality in forest stands from increasingly available high spectral resolution remote-sensing data.