Forest Ecology and Management 308 (2013) 76–89

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Forecasting potential bark beetle outbreaks based on spruce forest vitality using hyperspectral remote-sensing techniques at different scales

A. Lausch [a,*], M. Heurich [b], D. Gordalla [c], H.-J. Dobner [c], S. Gwillym-Margianto [d], C. Salbach [a]

[a] UFZ, Helmholtz Centre for Environmental Research - UFZ, Department of Computational Landscape Ecology, Permoserstraße 15, D-04318 Leipzig, Germany
[b] Bavarian Forest National Park, D-94481 Grafenau, Germany
[c] Leipzig University of Applied Science – HTWK Leipzig, Karl-Liebknecht-Straße 132, D-04277 Leipzig, Germany
[d] UFZ, Helmholtz Centre for Environmental Research - UFZ, Department of Community Ecology, Theodor-Lieser-Straße 4, D-06120 Halle, Germany

ARTICLE INFO

Article history:
Received 20 March 2013
Received in revised form 23 July 2013
Accepted 24 July 2013
Available online 23 August 2013

Keywords:
Bark beetle
Ips typographus (*L.*)
Hyperspectral remote sensing
Vitality
Attack
Spruce forest

ABSTRACT

The bark beetle (*Ips typographus L.*) is known for the detrimental impact it can have on Europe's mature spruce forests with bark beetle outbreaks already having devastated thousands of hectares of spruce forests in Germany. This study analysed the hypothesis that the vitality of spruce vegetation is already susceptible from factors such as climate change or emissions to a certain extent before infestation, so that the role of the subsequent bark beetle infestation is only secondary.

Hyperspectral remote-sensing techniques were used to detect changes in biochemical–biophysical vegetation characteristics in the spruce forest of the Bavarian Forest National Park, Germany. For this study, several spectral bands, vegetation indices and specific spectral band combinations of hyperspectral HyMAP remote-sensing data with a 4 m and a 7 m ground resolution were analysed and compared in terms of their classification accuracy, generating an ID3 decision tree.

The vitality classes and thus also the attack stages of the spruce vegetation could be estimated with moderate to good accuracy using hyperspectral remote-sensing data. Clear spectral differences between the class with spruce trees that were still green but with reduced vitality (possibly the first stages of green-attack) and the class with healthy spruce trees could be ascertained. The best spectral characteristics, spectral indicators and spectral derivatives related to vitality classes and thus attack stages were typically based on wavebands related to prominent chlorophyll absorption features in the VI within the spectral range of 450–890 nm. Only limited spectral information and derivatives could be found in the short-wave infrared region 1 (SWIR) within the spectral range of 1400–1800 nm, which reflects the water content of the spruce needles. The class of spruce trees that were still green but with reduced vitality (possibly the first stages of green-attack) showed a trend towards detectability and differentiation with spectral indicators and index derivatives. However, the prediction of observed effects with 64% accuracy as observed here is regarded as insufficient in forestry practises. Hyperspectral data with a ground resolution of 4 m were found to contain more information relevant to estimating the vitality class of spruce vegetation compared to hyperspectral data with a ground resolution of 7 m.

1. Introduction

In Europe and North America, forests are experiencing some of the worst outbreaks of insects in history. It therefore comes as little surprise that bark beetles (Scolytinae) are often considered to be one of the most significant pests in forestry. Not only can bark beetle outbreaks have devastating impacts on the lumber industry, but they are regarded by some to be one of the most significant natural disturbances to spruce forests (Schelhaas et al., 2003; Raffa et al., 2008). For this reason, Slobodyan and Slobodyan, 2001 also refer to the European spruce bark beetle (*Ips typographus L.)* as a biological indicator of disturbances in the functioning of forest ecosystems.

In Europe 154 species of bark beetle are known, whereby each species is adapted to only one or a few host tree species. The European (or eight-spined) spruce bark beetle *Ips typographus* is known to infest conifers – predominantly spruces (*Picea abies L.*). In the European spring time (March/April) the adult bark beetles start to swarm from daytime temperatures around 16.5°C.

* Corresponding author. Tel.: +49 341 235 1961; fax: +49 341 235 1939.
E-mail address: Angela.Lausch@ufz.de (A. Lausch).

0378-1127/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.foreco.2013.07.043

Subsequently, they attack spruces (*Picea abies L.*) and lay their eggs beneath the bark, where the larvae hatch and start to eat away at the inner bark of the infested trees. This feeding behaviour attacks the living phloem tissues of the trees, meaning that the transport of nutrients from the leaves to the roots is increasingly impaired. Due to this secondary starvation of nutrients in the leaves, there is a gradual reduction in chlorophyll and ultimately chlorophyll decay (Marx, 2010). From the middle of June through to the end of July the imagoes then leave their host tree and attack new spruces in their second generation. Trees that have only recently been infested are still green (green-attack), with the reddish-brown colouring of the spruce crowns (red-attack) only occurring after the beetles have already left the host tree that was used for breeding.

The devastating impacts of bark beetle on working forests have prompted research to improve our understanding of the different behaviour patterns and outbreak behaviour of bark beetles. For example Rossi et al. (2009), Avtzis et al. (2012) and Six (2012) have investigated the biology, development, ecology and phylogeography of different bark beetle species. From a different approach, the spatial distribution and pattern of *I. typographus* populations in Europe has been analysed by Heurich et al., 2003, Meier et al. (2003), Müller et al. (2008), Ogris and Jurc (2010) and Lausch et al. (2011, 2013). In addition, a number of other investigations have been conducted for North America (Powers et al., 1999; Negron et al., 2000; Klutsch et al. 2009) and Canada (Wulder et al., 2006a; Aukema et al., 2008; Coops et al., 2009). Due to this imminent threat, there has also been a recent research focus on monitoring bark beetles, in particular the efficiency of different monitoring techniques and strategies of bark beetle (Jurc et al., 2006; Meurisse et al., 2008; Saeed et al., 2010). Various systems have already been tested to monitor bark beetle infestations such as pheromone beetle traps (Liu and Dai, 2006), trap trees (Zumr and Stary, 1993) and spruce stand transects walked by foresters (Marx, 2010). Consequently, important information can be collected about the current infestation situation, its progression as well as swarming behaviour (Saeed et al., 2010). However, the disadvantage of such monitoring techniques is that they are not only time-consuming but also costly and thus unsuitable for forest stands that are larger than 2000 ha (Marx, 2010). Standardised methods therefore need to be established that enable a timely and cost-effective monitoring of the presence, distribution and outbreak potential of the bark beetle in spruce forests.

Remote-sensing techniques could provide the answer, as they have already been used to directly map and assess different issues of bark beetle and spruce vegetation behaviour characteristics. Numerous studies using remote-sensing techniques have concentrated particularly on the recognition and detection of the earliest bark beetle infestation of spruce. Depending on the length of the bark beetle attacks, one is able to differentiate between the different stages of bark beetle attack of the spruce vegetation. Trees that have only been infested very recently are still green (green-attack), while the reddish-brown colouring of the spruce crowns (red-attack) usually occurs when the beetles have already left the host tree used for breeding. It is only 36 months after the bark beetle attack that the spruces start to appear grey in colour (grey-attack). The symptoms of changes in biochemical–physical parameters of spruce vegetation with red and grey attack has been proven using remote-sensing techniques (Franklin et al., 2003; Skakun et al. 2003; Wulder et al., 2006a). However, so far research on "green attack" detection using remote-sensing sensors has been inconclusive, with forest managers still relying on high spatial resolution data of red-attack for planning ground surveys to establish green-attack and for implementing mitigation actions for infested areas.

Bark beetle outbreak pattern analysis and assessment based on MODIS time-series data (Eklundh et al., 2009), Landsat TM (Thematic Mapper) data (Coops et al. 2006, 2009; Wulder et al. 2006b; Hais and Kučera, 2008) and SPOT data has also been conducted by Wulder et al. (2006a). Furthermore, high spatial resolution data such as GeoEye-1 (Dennison et al., 2010), Ikonos (White et al. 2005), RapidEye (Marx, 2010) and Quickbird multispectral image (Hicke and Logan, 2009), Hyperspectral Mapper data (HyMAP, Hatalla et al., 2010; Fassnacht et al. 2012) have been used to detect and assess canopy mortality during mountain pine beetle outbreaks.

It can therefore safely be said that remote-sensing techniques have so far been used successfully to monitor spruce stands already infested with bark beetle. Currently however we are not aware of any available method that uses remote-sensing techniques to assess or predict potential areas of bark beetle infestation in the future. It is well-known that healthy forests are carbon sinks, but forests that are killed by bark beetles release carbon, turning them into significant carbon sources. An anticipation of where potential outbreaks might occur could assist policy-makers with climate change mitigation, by preserving forest carbon stocks as a result of implementing measures aimed at preventing bark beetle attacks in those areas where outbreaks can be predicted from hyperspectral remote-sensing.

It could be feasible to record or predict potential areas of bark beetle infestation when the following hypothesis can be applied and quantified using remote-sensing techniques.

Local capture experiments with the bark beetle have shown that the infestation of spruces by no means occurs systematically (Fahse and Heurich, 2011), but are rather subject to infestation criteria, on which there is still insufficient knowledge.

- According to Fahse and Heurich (2011) when there is an outbreak of bark beetle in a region, the predisposition of the spruce vegetation does not play a role in bark beetle infestation in a subsequent year. When the beetles invade, it is rather the case that the beetles "randomly" infest all trees.
- With a low level of bark beetle infestation in a region, however the predisposition of the spruce trees does play a large role in bark beetle infestation in a subsequent year. At times that are not during an outbreak there are not enough beetles available to trigger off an infestation of healthy trees. The beetles are thus restricted to engaging in a reproductive strategy that involves the "*selective infestation*" of trees that are already weak (Fahse and Heurich, 2011).

In the case of a "selective infestation of spruces" Fahse and Heurich (2011) suppose that the spruces have already been so damaged in terms of their vitality due to various factors i.e. climate change, a systematic increase in temperature, a reduction in the ground water level and thus the supply of water, as well as an increase in ozone and particle emissions, that the subsequent bark beetle infestation should only be regarded as a secondary event i.e. the bark beetle can be regarded as a secondary pest.

Progressive climate change as well as high levels of air pollution can lead to severe changes in the context of the bark beetle. Progressive warming as well as a lack of water over longer periods of time reduces the "health" or "vitality" of spruce forests. This makes the spruces more susceptible to an attack from *Ips typographus* (Ohrn, 2012). The after-effects are evident. Insects such as *I. typographus* rely on the temperature for their metabolism and population development. An increase in the mean temperature can result in an earlier onset of the flight of spruce bark beetle in the spring. Moreover, an increase in the mean temperature means that the eggs hatch sooner i.e. they develop into adults sooner, leading to a faster development of a second generation (Jönsson et al., 2007, 2009; Faccoli, 2009; Ohrn, 2012). Furthermore, high elevation spruce forest ecosystems like the Bavarian National Park in