Remote sensing of bark beetle damage in urban forests at individual tree level using a novel hyperspectral camera from UAV and aircraft

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ABSTRACT

Climate-related extended outbreaks and range shifts of destructive bark beetle species pose a serious threat to urban boreal forests in North America and Fennoscandia. Recent developments in low-cost remote sensing technologies offer an attractive means for early detection and management of environmental change. They are of great interest to the actors responsible for monitoring and managing forest health. The objective of this investigation was to develop, assess, and compare automated remote sensing procedures based on novel, low-cost hyperspectral imaging technology for the identification of bark beetle infestations at the individual tree level in urban forests. A hyperspectral camera based on a tunable Fabry-Pérot interferometer was operated from a small, unmanned airborne vehicle (UAV) platform and a small Cessna-type aircraft platform. This study compared aspects of using UAV datasets with a spatial extent of a few hectares (ha) and a ground sample distance (GSD) of 10–12 cm to the aircraft data covering areas of several km² and having a GSD of 50 cm. An empirical assessment of the automated identification of mature Norway spruce (Picea abies L. Karst.) trees suffering from infestation (representing different colonization phases) by the European spruce bark beetle (Ips typographus L.) was carried out in the urban forests of Lahti, a city in southern Finland. Individual spruces were classified as healthy, infested, or dead. For the entire test area, the best aircraft data results for overall accuracy were 79% (Cohen’s kappa: 0.54) when using three crown color classes (green as healthy, yellow as infested, and gray as dead). For two color classes (healthy, dead) in the same area, the best overall accuracy was 93% (kappa: 0.77). The finer resolution UAV dataset provided better results, with an overall accuracy of 81% (kappa: 0.70), compared to the aircraft results of 73% (kappa: 0.56) in a smaller sub-area. The results showed that novel, low-cost remote sensing technologies based on individual tree analysis and calibrated remote sensing imagery offer great potential for affordable and timely assessments of the health condition of vulnerable urban forests.

1. Introduction

Drivers of global climate change may affect urban woodlands more rapidly than natural forest ecosystems. Stressors of urban forest ecosystems include alterations in forest soils and to the diversity and composition of the urban ecosystem, as well as higher temperatures and early springs since 2010 (P. Lyytikäinen-Saarenmaa, 2006; Aukema et al., 2011). Proactive management practices and a focused novel monitoring methodology are needed to protect urban forests against the threats posed by insect pests.

One of the most significant threats to boreal forests is climate-related extended outbreaks and range shifts of the destructive bark beetle species (e.g., Safranyik et al., 2010; Kärpänen et al., 2016; Ghimire et al., 2016). In Finland, the European spruce bark beetle (Ips typographus L.) has been undergoing a poleward range shift as a damage-causing agent due to elevated summer temperatures and early springs since 2010 (P. Lyytikäinen-Saarenmaa, 2006; Aukema et al., 2011). The European spruce bark beetle (Ips typographus L.) is a destructive pest that causes extensive ecological damage and economic costs to urban woodlands, either through the direct or indirect effects of climate change on insects (Lyytikäinen-Saarenmaa et al., 2006; Aukema et al., 2011). Proactive management practices and a focused novel monitoring methodology are needed to protect urban forests against the threats posed by insect pests.

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unpublished data). Climatic anomalies, such as more frequent and intensive heavy winds and prolonged periods with low amounts of precipitation, have resulted in a multitude of windthrows and stressed Norway spruces (Picea abies Karst.). These trees provide optimal breeding material for bark beetles, facilitating the elevating population levels. Consequently, expansive damage spots with visible crown symptoms are present in southern and central parts of Finland, threatening the sustainability of mature Norway spruce stands. It is important to identify colonized trees at an early phase and initiate management operations to protect healthy stands. Bark beetles can cause dramatic, irreversible alterations both in natural and urban forest environments. Especially in urban forests, it is of great importance to maintain safe pathways and aesthetic values, because forests in such areas enjoy high levels of recreational use by citizens.

The vision for the future of precision forestry includes storing forest information at the individual tree level in geographical information systems (GIS) (Holopainen et al., 2014). Such systems are already available or currently being created for urban areas in many Finnish cities (Tanhuanpää et al., 2014). The database should include information about tree locations and various attributes, such as species, height, and stem volume. Several efficient remote sensing technologies are now available for providing this information, including airborne-, mobile-, and terrestrial laser scanning (ALS, TLS, MLS) and stereo imagery (White et al., 2016). Information on tree health and quality are more demanding to measure and typically obtained using multi- or hyperspectral technologies or field measurements (Hall et al., 2016; Senf et al., 2017). Furthermore, since these parameters can change rapidly, the methods affordable for frequent, annual monitoring are of great interest, particularly in small-scale urban woodlands.

Recent developments in multi- and hyperspectral remote sensing technologies are providing new solutions for vegetation health mapping (Torresan et al., 2017). In particular, developments in miniaturized sensor technologies have facilitated the production of low-cost and lightweight multispectral and hyperspectral cameras that enable accurate remote sensing measurements. Several light-weight hyperspectral sensors have already been developed (Aaasen et al., 2015). One type of camera is based on the Fabry–Pérot interferometer (FPI) technique (Mäkynen et al., 2011; Honkavaara et al., 2013; Oliveira et al., 2016) and was used in this study. This technology has already shown potential in close-range environmental mapping with unmanned aerial vehicles (UAVs), such as monitoring the health of vegetation (Näsi et al., 2015; Moriya et al., 2017) and classifying tree species (Nevalainen et al., 2017). Important advantages of the FPI technology in comparison to the conventionally used pushbroom technology include the possibility to collect image blocks with stereoscopic multiple object views; the important consequences of which include more extensive datasets, a simplified data processing phase, and reduced costs to the overall system (Honkavaara et al., 2013).

Lightweight, low-cost hyperspectral sensors combined with cost-efficient platforms, such as single-engine manned aircraft or UAVs, offer a tool for the timely monitoring and identification of insect-induced alterations in forest vegetation (Lehmann et al., 2015). Both platforms have their pros and cons with respect to environmental remote sensing tasks. UAVs typically have to be operated in the visible line-of-sight at low flight altitudes due to legislative issues. As a result of these requirements, multicopters are the most useful vehicles for such tasks because they can be used for repeated high-resolution mapping tasks within small areas (Siebert and Teizer, 2014). Small aircrafts are efficient in covering larger areas; on the other hand, their initialization cost is more expensive and they produce lower spatial resolution data than UAVs. The low-cost methods can revolutionize the entire environmental remote sensing process. The conventional high-end hyperspectral sensors are typically expensive and rare, thus obtaining data from these systems can be more difficult and costly. In contrast, these low-cost systems can be owned and operated locally by small companies, thus making it easier to organize remote sensing campaigns and also multitemporal monitoring acquisitions.

A review by Senf et al. (2017) showed that recent research related to the remote sensing of insect pest damage has focused on conifer bark beetles and defoliators of deciduous trees. Among bark beetles, the mountain pine beetle (Dendroctonus ponderosae Hopkins) in North America and European spruce bark beetle (I. typographus) are the most studied insect pests, especially in the last few years. Satellite images, such as Landsat (Havasová et al., 2015; Foster et al., 2016; Long and Lawrence, 2018), have been the most utilized, whereas hyperspectral sensors have been used only in a few studies (Senf et al., 2017). Näsi et al. (2015) were the first to utilize UAV-based hyperspectral image data for identifying different infestation stages of the bark beetle. Their results showed that different stages (i.e., healthy, infested, and dead trees) could be identified by machine vision technologies based on hyperspectral UAV imaging at the individual tree level; the results for the overall accuracy were 76% when using three color classes (healthy, infested, dead). For two color classes (healthy, dead), the best overall accuracy was 90%. Their conclusions were that survey methodology based on high-resolution hyperspectral imaging will be of great practical value for forest health management, capable for instance of indicating the potential for a bark beetle outbreak at a particular time.

Studies using conventional pushbroom scanning-based hyperspectral sensors from aircraft platforms for the mapping of bark beetle damage using area-based methods have shown promising results. Fassnacht et al. (2014) reported an overall accuracy rate of 76–85% when three health classes of trees and two types of soil were classified. Lausch et al. (2013) were able to classify three health classes with an overall accuracy rate of 69%. Only a minor proportion of studies on bark beetle damage have used high spatial resolution (ground sample distance, GSD < 1 m) data (Senf et al., 2017), which is a prerequisite for individual tree-level approaches. Meddens et al. (2011) and Lausch et al. (2013) have reported that enhancing the spatial resolution of remote sensing images improves the classification results for bark beetle damage. However, in both studies researchers performed their analysis at the area or pixel level as opposed to adopting an individual tree-level-based approach. Recent developments in sensors and UAV technologies are enabling analysis at the individual tree level because many pixels can be obtained from each tree due to the small GSD. However, only a few studies have analyzed pest damage at the individual tree level. For example, Minafik and Langhammer (2016) presented preliminary results using a UAV equipped with a multispectral sensor to map bark beetle damage and Dash et al. (2017) used a multispectral sensor to classify a disease outbreak in mature Pinus radiata D. Don using a UAV as a platform. More information about state-of-the-art remote sensing of forest insect damage can be found in the extensive reviews provided by Hall et al. (2016) and Senf et al. (2017). Furthermore, Lausch et al. (2016, 2017) have presented comprehensive reviews of remote sensing methods used to assess forest health that cover various types of damage, including insect damage, drought, invasive species, air pollution, and land-use changes.

The fundamental motivations for this investigation were to assess whether or not low-cost FPI camera technology can provide useful remote sensing data on the health of spruce trees in urban forests via aircraft or a UAV platform and to compare these two platforms. The same camera was operated using aircraft over an area of several square kilometers as well as a small UAV to identify symptoms in small areas. Accordingly, our main goals were to i) develop and assess a novel, low-cost, miniaturized, hyperspectral remote sensing technology for observing bark beetle infestation at the individual tree level in urban Norway spruce stands, ii) compare automated remote sensing procedures when operated from UAV and aircraft platforms.

The preliminary analyses of the UAV datasets were presented by Näsi et al. (2015). The current work emphasizes the aircraft data analysis and comparison of the UAV and aircraft results as well as production of spruce health maps. This study provides new information about the applicability of novel remote sensing technologies for tree
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