CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

DETECTION OF FOREST INFECTIONS USING UNMANNED AERIAL VEHICLE

Tomáš Klouček
Jan Komárek
Ondřej Lagner
Michal Fogl
Kateřina Gdulová

T A Č R
Technologická agentura České republiky

ČZU
ČESKÁ ZEMĚDĚLSKÁ UNIVERZITA V PRAZE

Detection of forest infections using unmanned aerial vehicle

Certified methodology

Autors

Mgr. Ing. Tomáš Klouček, Ph.D.

Ing. Jan Komárek, Ph.D.

Mgr. Ing. Ondřej Lagner

Ing. Michal Fogl

Ing. Kateřina Gdulová

Department of Applied Geoinformatics and Spatial Planning, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, Prague – Suchdol, 165 00

Professional reviewers

Ing.NorbertBuchta[1]

Ing. Stanislav Slanina, Ph.D.[2]

[1]*The Forest Management Section,*

The Ministry of Agriculture of the Czech Republic, Těšnov 65/17, Prague 1, 110 00

[2] *PEFC Czech Republic, Bělohorská 274/9, Prague 6, 169 00*

Acknowledgment

The methodology was created with the support of the Technology Agency of the Czech Republic (TA ČR) project No. TJ01000428 - Detection of infection forest bark beetle (*Ips typographus)* in advance using unmanned air vehicles; CZU internal grant (monitoring spatial-temporal dynamic by satellites, project no. CIGA20184206) and the international project COST (European Cooperation in Science and Technology) No. CA17134 - Optical synergies for spatiotemporal sensing of scalable ecophysiological traits.

Thanks to Priv.-Doz. Ing. Peter Surový, Ph.D. from the Department of Forest Management of the Faculty of Forestry and Wood Sciences CULS in Prague for collaboration and patient cooperation. We thank our colleagues Ing. Přemysl Janat, Ph.D., Ing. Bedřich Vašíček and Ing. Václav Jans from the KRNAP Administration for the cooperation so far and ongoing affection. We would like to thank also to doc. Ing. Petra Šímová, Ph.D. for patience, freedom and a helpful approach in solving the project and bark beetle problematics.

Application and storage

An agreement on the application of the methodology was concluded between the provider of the methodology, the Czech University of Life Sciences Prague, and the user, the Administration of the Krkonoše Mountains National Park.

The methodology is stored at the Czech University of Life Sciences Prague, the Administration of the Krkonoše Mountains National Park in Vrchlabí and at the grant provider Technology Agency of the Czech Republic (TA CR).

kůrovec

kurovec.czu.cz

1 Introduction

The ongoing climate change has, among other things, a major impact on the disturbances of forest ecosystems, which is significantly associated with the current bark beetle calamity caused mainly by the European spruce bark beetle (Raffa et al., 2008; Näsi et al., 2015). The bark beetle calamity significantly affects the productive function of the forest, at the same time it also affects its ecological function associated with water retention in the landscape, nutrient and carbon storage (Edburg et al., 2012) or biodiversity protection (Müller et al., 2008). The bark beetle calamity significantly disturbs the balance of forest stands and thus the entire forest ecosystem (Bright et al., 2014). Temperate coniferous forests are becoming one of the most endangered ecosystems on our planet (Seidl et al., 2017). Many scientific studies aim to find any suitable tool that would eliminate or at least slow down the spread of the European spruce bark beetle. Increased attention has been paid to this issue in recent years, yet there is no comprehensive and effective solution. At the same time, the detection of infestation of stands (at the level of individual trees) is important not only for economic but also for the above-mentioned ecological reasons (Fassnacht et al., 2014; Senf et al., 2015; Hais et al., 2016). The European spruce bark beetle (*Ips typographus*), hereinafter referred to as the spruce bark beetle, is a significant secondary insect pest of forestry (Fassnakh et al., 2014; Latifi et al., 2014a). It belongs to the order of beetles, which significantly contribute to biotic forest disturbances not only in Central European stands (Christiansen & Bakke, 1988). The spruce bark beetle (see Fig. 1.1) is a flying beetle that grows to about 5 mm and feeds on bast. The bast, as a part of the vascular bundles, is a key structure for the tree, which enables the distribution of water and nutrients. The outbreaks usually begin with the end of spring, when the beetles begin to swarm from their wintering grounds. Adults usually attack physiologically weakened or damaged spruce trees (*Picea abies*).

The tree can withstand the attacks of beetles using autoregulatory mechanisms, such as the use of resin to eliminate the attacker. Under normal circumstances, the spruce bark beetle is a desirable solution for rejuvenating forest stands and a factor in the good health of the forest. However, in the case of outbreaks of a beetle, the tree cannot withstand the increased number of attackers and there is a mass infestation of trees. The result of the infestation is the gradual drying of the trees and its subsequent death. Depending on the habitat and climatic conditions, swarming of the spruce bark beetle can take place several times a season (Fassnacht et al., 2014; Latifi et al., 2014a).

Figure 1.1: The spruce bark beetle activity; capturing larvae and adult phase Source: own

The ongoing bark beetle calamity in Central Europe is the result of an extreme overgrowth of the spruce bark beetle. The increased condition is mainly helped by the large proportion of older contemporaneous monocultures of spruce and in recent years also significantly warmer and drier climatic conditions not only during the swarming season (Marini et al., 2017). The intensity of the spruce bark beetle attacks reflects the health of the vegetation (terpenes of the weakened tree are an attractant for the spruce bark beetle) as well as the local climate. Effective defensive measures are the removal of all infested wood before the development of the beetle is completed and the processing of wood suitable for its further development. The spruce bark beetle is also purposefully eliminated in foci of infestation using traps (pest control). Although the spruce bark beetle also has several natural enemies and predators (Christiansen & Bakke, 1988), its current overpopulation is a very serious risk to all forest ecosystems.

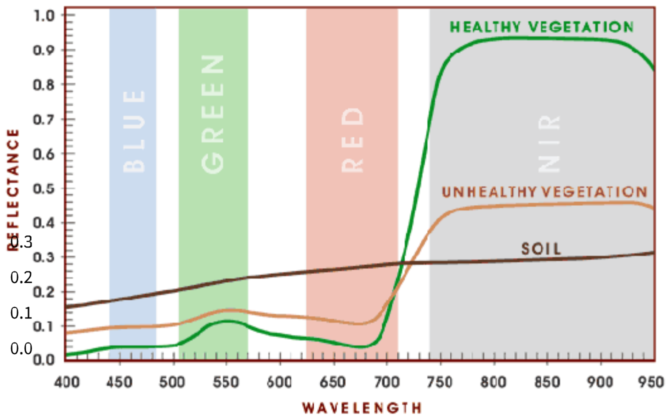
The key to removing infested wood is to find it in time. After a successful attack by the spruce bark beetle, wood material originating from boreholes in a form of brown dust is visible in the trunk of the tree. The brown dust is observable to the eye during the errands of the forest manager. A more pronounced manifestation of the spruce bark beetle infestation is the falling bark of the tree and later the change in the colour of the needles (yellowing). However, these manifestations are often associated with the fact that the development of the beetle has already been completed. The most effective way of defence is the elimination and remediation of infested wood before the development of the beetle is completed, in the phase when the crown is green and the bark does not fall off. Therefore, in addition to field research, it is also appropriate to use Earth remote sensing techniques (satellite systems, unmanned aerial vehicles, etc.) to increase the detection efficiency (Meigs et al., 2011; Meddens et al., 2013). An overview of current work dealing with the study of insect disturbances, which also includes the issue of the spruce lichen-eater, is summarized, for example, by remote sensing of the Earth (Senf et al., 2017).

Detection of an infested tree by remote sensing techniques involves observing changes in the spectral properties of the tree (Näsi et al., 2015; Abdullah et al., 2018). Spectral properties can be understood as the ability of a tree to reflect incident radiation in different parts of the electromagnetic spectrum (Jones & Vaughan, 2010; Lillesand et al., 2015). The reflectivity of different surfaces depending on the wavelength of the incident radiation can be described by the so-called spectral curve.

A healthy tree exhibits the characteristic shape of a spectral curve, and a change in its health results in a change in the shape of the spectral curve across the entire electromagnetic spectrum (Abdullah et al., 2018), see Figure 1.2. The potentially most suitable part of the spectrum for the study of vegetation and its health is the near-infrared band (NIR). The NIR band is sensitive to changes in chlorophyll content (for example in the leaves or needles of trees). Reflectivity in the NIR band is therefore an important indicator of the health of vegetation, which is directly related to the detection of trees infested with insect pests. The NIR band can be used alone or in combination with other spectral bands - then we talk about the so-called spectral / vegetation indices (Bannari et al., 1995).

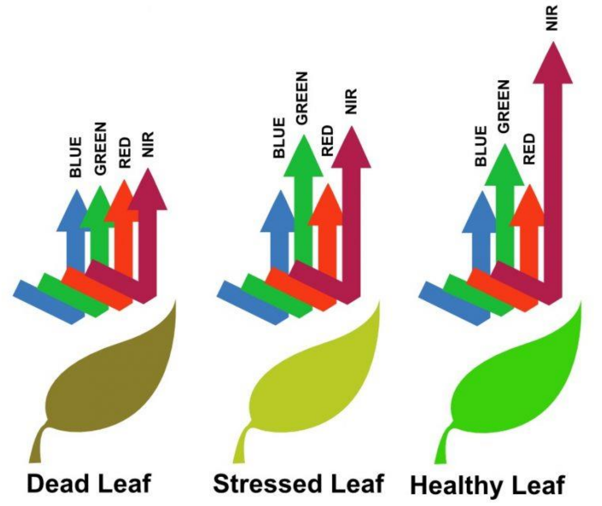
Figure 1.2: Spectral curve of healthy vegetation (green), stressed vegetation (orange) and soil curves (brown); reflectivity of objects in different parts of the electromagnetic spectrum

Source: http://physicsopenlab.org



A standard digital camera captures the image in three parts of the spectrum - blue (Blue), green (Green) and red (Red), by customizing the camera, it is possible to capture also in the NIR band. A prerequisite for using the principle of changes in the spectral expression of a tree is the hypothesis that tree infestation will be more significant in the NIR band (see Fig. 1.3) than in other parts of the spectrum (RGB) observable to the human eye. When fulfilling this assumption, the infested tree can be detected earlier (in a shorter time after insect infestation) before there are clearly visible visual manifestations of infestation (discolouration of needles, bark decay, etc.). In addition to conventional digital cameras, professional multispectral (Medens et al., 2013; Latifi et al., 2014a, b; Senf et al., 2015; Hais et al., 2016) or hyperspectral sensors (Lausch et al., 2013; Fassnacht et al., 2014) placed on satellites, unmanned aerial vehicles (Näsi et al., 2015; Minařík & Langhammer, 2016; Brovkina et al., 2018; Marina et al., 2018) or aircraft platforms (Bright et al., 2013, 2014) could be used. However, the above mentioned remote sensing platforms and sensors are not suitable for practical application in early detection of infestation of individual trees not only by the spruce bark beetle for several reasons (see Tab. 1.1): insufficient spatial (high-resolution multispectral satellite data) or temporal resolution (freely available periodically acquired satellite data), high acquisition prices of data/sensors (very high-resolution satellite data, professional UAV sensors)

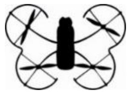
Figure 1.3: Spectral manifestation of vegetation



Source: http://www.agasyst.com/portals/NDVI.html

Therefore, the use of unmanned aerial vehicles (UAVs) in combination with conventional digital cameras is the most suitable solution for detailed analyzes. The UAV platform offers variable time resolution and a common (modified NIR) digital camera provides a suitable combination of spatial resolution (allowing delimitation of individual trees) with sufficient spectral resolution necessary to monitor the health of vegetation. At the same time, conventional digital cameras, compared to professional sensors, are a very economically acceptable solution. The usability of this technology was confirmed by the authors of the methodology in a previous scientific study, which shows that even a low-cost UAV camera can monitor changes in spectral reflectivity several weeks after the tree was attacked by the spruce bark beetle.

Table 1.1: Platform features and examples of studies using specific platform and sensor; distinguished by a range of symbols, more symbols means higher/larger

		-	
			
Coverage	- - -	- -	-
Spatial resolution	-	- -	- - -
Temporal variability	-	- -	- - -
Independence from the weather	- - -	- -	-

Source: own

2 Objectives of the methodology

The methodology aims to create a comprehensive procedure for the detection of infestation of forest stands by back beetle (*Ips typographus)* using unmanned aerial vehicles (UAV). The methodology describes all steps leading to the successful identification of infested trees, i.e. acquisition of data using a suitable camera (sensor) located on an unmanned aerial vehicle, basic processing of scanned UAV data, and (semi) automatic detection of infestation on individual trees. Based on the methodology, the user will be able to identify with sufficient credibility the potentially infested trees by bark beetle and apply appropriate forestry measures within the framework of sustainable forest management.

3 Description of methodology

The methodology is divided into four parts, (A) Acquisition of UAV data and their processing, (B) Preprocessing of UAV data, (C) Detection of (un)infested trees and (D) Summary scheme and specific example of data processing. The methodology does not aim to create one generally applicable solution, which is not realistic due to the diversity of potentially usable UAV platforms and sensors, processing software or the specificity of each site of interest. The methodology always recommends several differently demanding approaches to the user, based on which it is possible to detect individual trees infested with the spruce bark beetle using UAV data. The methodology allows the user to choose from his point of view (processing, economic complexity, required accuracy, etc.) the most suitable solution.

A necessary condition for the successful applicability of the methodology is at least basic knowledge in the areas of remote sensing, photogrammetry and digital analysis of image data and related processing software.

3.1 PART A: Acquisition of UAV data and their processing

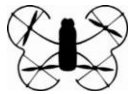
Platforms and sensors

Any aerial platform can be used to capture data. Depending on the size of the area of interest, two types of unmanned aerial vehicles can be recommended from a methodological point of view as suitable UAV platforms (sensor carriers) (see Table 3.1). For areas with a smaller size of units up to tens of hectares, so-called multicopters can be used. Multi-rotors controllability is regulated by the speed of each rotor.

For larger land units (of tens to hundreds of hectares), we recommend using the wing type of unmanned system with a lift. Both mentioned systems are interchangeable, and the choice depends on the specific habitat conditions and capabilities of the user. It is also up to the user to choose a commercial solution or a solution that requires user intervention. Commercial solutions are usually ready for a specific application, and usually, the device and control system is ready for immediate operation without the need to install or set up the application. In contrast, free solutions require a degree of expertise and user experience with unmanned systems, as well as advanced control software capability.

However, these solutions offer higher variability with payload, so the user can equip the device with the camera/sensor he needs. Unfortunately, in commercial solutions, this possibility is considerably limited, and the user is dependent on the manufacturer of the specific unmanned vehicle that determines the supported cameras/sensors. A comparison of commercial and free systems is offered by Moudry et al. (2018). The usability of UAVs for detailed vegetation mapping is confirmed in their study by, for example, Komárek et al. (2018).

Table 3.1: Properties of multi-rotor and wing aircraft; resolution by a range of symbols, more symbols means higher / larger

		
Flight speed	▪ ▪ ▪	▪ ▪
Coverage	▪ ▪ ▪	▪
Spatial resolution	▪ ▪	▪ ▪ ▪
Take-off and landing area	▪ ▪ ▪	▪
Flight time / endurance	▪ ▪ ▪	▪ ▪

Source: own

As well as the choice of platform, the selection of the appropriate sensor (camera) is a matter of circumstances and depends on the user's capabilities. To achieve adequate results, the selected camera should capture near-infrared (NIR) radiation in addition to the visible part of the spectrum (RGB). There are several solutions on the market, from very expensive hyperspectral sensors for professional use to customized digital cameras with minimal costs. The use of professional solutions brings more accurate results, however, at disproportionately higher financial costs.

On the other hand, by modifying an ordinary camera, we achieve sufficient results at a reasonable cost. In our study, a user-modified digital camera was used. The modification consists in mechanically making the passage of NIR radiation to the camera's scanning surface accessible (see, for example, the instructions available on YouTube), which enables the camera to record images in the NIR band. Interference with the camera's sensing capabilities is irreversible and requires some technical knowledge of the user; unprofessional intervention can destroy the camera. The chosen solution thus depends on the dispositions and financial possibilities of the user.

From professional solutions, several proven types of sensors can be recommended. Here is a list of manufacturers and sensors that are commonly used in combination with unmanned aerial vehicles. These include Parrot (Sequoia model), MicaSense (RedEdge models), Airinov (MultiSPEC 4C), Tetracam (CAMCA model line). To achieve the best possible result, it is advisable to pair the selected sensor with a sensor that records information about the intensity of incident light, the so-called exposure (irradiation) sensor. Using the exposure intensity values, radiometric calibration of the images can be performed later. Radiometric calibration eliminates the effect of different exposure intensities during data collection, typically caused by alternating light and shadow on sunny days. Thanks to this calibration, it is also possible to compare data acquired in other locations, other times, etc. However, sufficient results can be achieved even without an exposure sensor using the appropriate data processing technique.

Flight mission planning

Planning a flight mission is a key step in using any sensor and platform. Before planning, it is necessary to find out about the national legislation concerning UAVs. Without following a few principles, the right pictures can´t be taken, even with the most expensive solutions. The output of the flight mission will be a set of images. The images will then be processed photogrammetrically, therefore the mutual overlap of adjacent images must be adhered to.

During the flight mission, it is necessary to ensure minimal longitudinal and transverse overlaps of the captured images (50–80% depending on the conditions, see Fig. 3.1). The size of the overlaps can affect both flight speed and altitude. It is also necessary to secure the minimum flight altitude so that the images can be combined into a mosaic. This step is especially important when planning a flight mission over a mature stand (forest). When determining the flight altitude, it is necessary to take into account the height of the stand, i.e. the height of the stand must also be added to the standard flight altitude (usually the flight altitude above the terrain is in the range of 80-120 m).

The device speed must provide sufficiently sharp images. Setting flight mission parameters is usually a matter of setting up control software, which can vary for different platforms and sensors. The list of recommended parameters is summarized in the table below (Table 3.2).

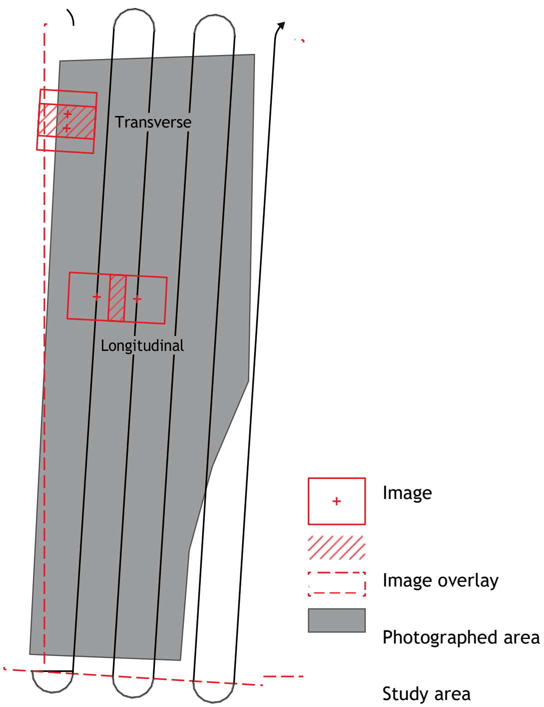
Table 3.2: Recommended flight mission planning parameters

Parameter	Value
Flight altitude above the surface	50–70m
Longitudinal overlay of images	60–80%
Transverse overlay of images	50–70%

Source: own

The flight mission also needs to be planned concerning weather conditions. One of the critical factors is the formation of icing, which significantly affects the performance and manoeuvrability of the drone. The operating temperatures of unmanned aerial vehicles usually range from −10 ° C to +40 ° C. However, icing conditions can occur even at temperatures above freezing point, especially at elevated humidity. The wind speed should not exceed 5 m/s without wind gusts to achieve sharp images.

Figure 3.1: Flight mission planning, resolution of transverse and longitudinal overlaps



Source: own

The specific parameters of resistance to climatic factors can be found in the technical specifications and operating manuals of each unmanned vehicle. The intensity of the incident light is also an important parameter (see radiometric calibration). The ideal preconditions for a flight mission are stable lighting conditions, i.e. constantly cloudy. Although clear weather might seem like a good option, the incident sunbeams generate a large number of shadows in the resulting image. The shadow can significantly reduce the number of pixels entering the subsequent analysis and thus affect the credibility of the results (see PART B). In the case of sunny weather, it is necessary to limit the flight mission to such a time that the angle of the incident rays does not distort the collected data so that the Sun is not too low or too high in the sky - the altitude angle limit should be observed in the range of 30 ° - 60 ° from the horizon.

The following is a list of selected applications for flight mission planning, compatibility with the platform must be specified in the user manual of the selected software. Mission Planner (Windows), Pix4Dcapture (Android and iOS), UgCS (Windows, Mac OS, Linux) can be used to plan a flight mission.

Flight mission timing

One of the important aspects of the detection of infested trees by the spruce bark beetle is the appropriate date (or time interval) of the acquisition of UAV images. The flight mission must be planned in such a way that the images distinguish the spruce bark beetle infested trees from the uninfested ones (while the distinctiveness of the infested tree increases with the time since its infestation) and also early enough for implementation of forestry measures in advance before the new generation of the spruce bark beetle of these trees leaves. However, due to the diversity and specificity of different localities of interest (climatic conditions, topography, altitude, etc.), the widely usable term (for example, how many days or weeks after the start of the new generation of spruce bark beetle activities to obtain data) cannot be clearly determined. Therefore, to achieve the most credible results, it is necessary to discuss the timing of taking pictures with forest managers. They have a perfect overview of the site of interest and can, based on their experience, expertly estimate the most suitable date of the flight mission, preferably before or with the appearance of the first visible symptoms on the infested trees. From the point of view of remote sensing of the Earth, it is possible to define a generally valid assumption that the more technologically advanced sensor (especially depending on the higher spectral resolution) we use, the more it is possible to detect signs of the attack earlier. To achieve the most reliable detection, it is also recommended to acquire one control flight mission before the activity itself (or each new generation) of the spruce bark beetle (see PART C).

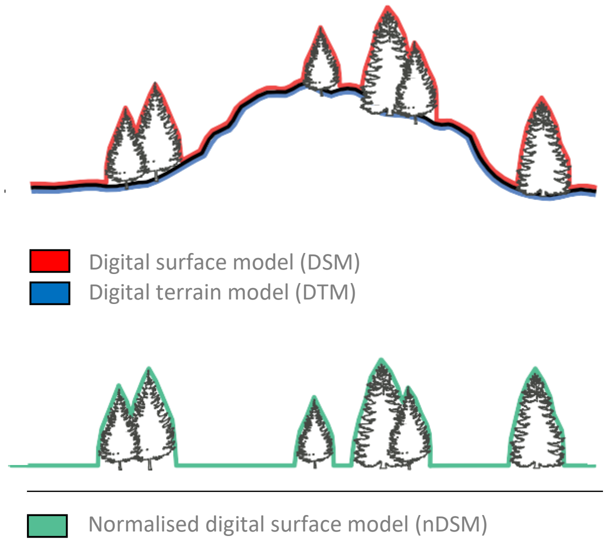
Processing of acquired data

Scanned data from unmanned systems are subject to photogrammetric processing, which allows to obtain three-dimensional information about the locality / object of interest from two-dimensional images. Currently, the Structure from Motion (SfM) - Multi View Stereo (MVS) imaging technique is widely used. Methods use identical points based on local extremes in images with central projection. Stable points are then assigned their orientation. Identical points are found at the locations of the image overlaps, so adjacent images can be linked this way. With points that are on several images at the same time, information about the spatial orientation of the images is then obtained. Furthermore, a sequential approach takes place to reconstruct the structure in the image. The result is information about the position of all images and the so-called point cloud, i.e. significant points with x, y, z coordinates.

Bundle block adjustment align the elements of external and internal orientation. Using image triangulation, the relationship between the image coordinates and the object coordinates is found, and image correlation creates the so-called dense point cloud. This is achieved by iteratively creating new adjacent points and subsequent filtering and eventual decimating the resulting point cloud. From the point cloud created in this way, it is then possible to perform a three-dimensional reconstruction of the scanned locality / object. If the selected sensor has an exposure sensor, it is advisable to calibrate the resulting mosaic radiometrically in the software (see chapter 1). Radiometric calibration transforms the values into surface reflectivity, which is suitable for further image analysis. For a successful transformation, the values of the incident intensity of exposure and the values of the so-called calibration target are needed. The target can be imagined as a plate with a material for which we know the spectral properties across the sensed electromagnetic radiation. There are several software using the SfM-MVS method. Both commercial solutions (eg Agisoft Photoscan, Pix4Dmapper, Reality Capture) and freely available solutions (Bundler, Visual SFM, SFMtooklit and others) are available.

The output from SfM image processing is a digital surface model (DSM) and an orthorectified mosaic. Orthorectification is a method of converting images by orthogonal projection into a map display, which uses the mentioned digital model to eliminate the displacement of points caused by relief. The digital surface model is a terrain model including the upper surfaces of all objects in the field (i.e. buildings, vegetation, etc.). According to the selected software, the DSM classification can also be used to obtain a digital terrain model (DTM), a representation of the earth's surface (without objects on it). These three products (mosaic, DSM and DTM) are key and necessary for further processing. Very important is also to obtain the so-called normalized model, i.e. to determine the height of objects above the terrain, see Fig. 3.2.

Figure 3.2: Representation of digital models: digital surface model (red), digital terrain model (light blue), normalized model (green), earth terrain (black)



Source: own

Recommendations for PART A - Acquisition of UAV data and their processing

In tab. 3.3 we present a list of recommended parameters and settings that lead to the creation of the corresponding outputs necessary for the next part of processing. These parameters were used in our study.

Table 3.3: Recommended parameters for section Acquisition of UAV data and their processing

Platforms and sensors	
Platform type	Multi-rotor platform
Sensor type	RGB camera + user modified NIR camera
Exposure sensor	not applied
Flight mission planning	
Flight height above stand	50 m
Longitudinal overlap	80%
Transverse overlap	60%
Meteorological conditions	No icing conditions, wind speed up to 5 m/s without wind gusts.
Data processing	
Software	Agisoft Photoscan Professional
Process steps	Image matching - Aligning
	Densification
	Mesh building
	DSM building
	Export DSM
	Orthomosaic building
	DTM classification
	DTM building
	Export DTM

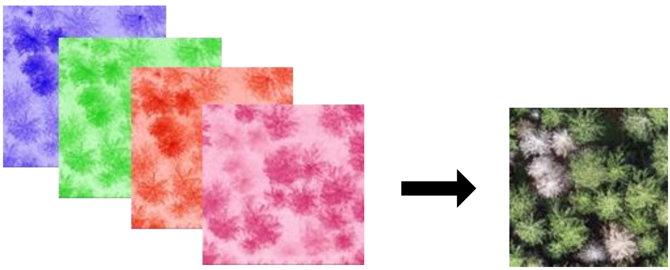
Source: own

3.2 PART B: Preprocessing of UAV data

Creating a multilayer file

Orthorectified (multi)spectral mosaics and digital surface (DSM) and terrain (DTM) models, which are the output of photogrammetric processing (PART A), are the input for subsequent image analysis (PART B and C). When using a multispectral camera, the output (depending on the selected processing software) will most often be one multi-layer file (for example in * .tif format) containing spectral mosaics in which the camera scans the spectral bands. These can then be displayed in a digital environment, for example using so-called colour synthesis (Fig. 3.3), etc. Typically, sensors made for unmanned aerial vehicles are sensing in the Green (G), Red (R), Red Edge (RE), and Near Infrared (NIR) part of the spectrum, but hyperspectral sensors sensing in tens to hundreds of narrow spectral bands can also be purchased. Using a conventional RGB camera and a user-modified NIR camera, will most likely result in two mosaics (taken from data obtained by two individual UAV flight missions), one containing RGB bands and the other NIR. In this case, it is first necessary to merge the two mosaics together and create a multilayer file (Fig. 3.3).

Figure 3.3: Example of creating a multilayer file and its display using colour synthesis in the so-called true colours (ENVI software)



Source: own

Radiometric calibration

Calibrated data are an important prerequisite for the reliability of spectral index values, results of detailed classification of image (not only UAV) data or direct time comparison of a pair of images, spectral indices, etc. (Song et al., 2001). If the resulting mosaic is not radiometrically calibrated (using calibration targets and a sensor measuring the intensity of incident solar radiation) to the surface reflectance values in the photogrammetric processing process, it is desirable to perform the calibration additionally. If the calibration is not performed, the reliability of the achieved detection cannot be fully declared, even if the other methodological steps are followed. In the case of sensors measuring in all spectral bands at once (multispectral, hyperspectral cameras, etc.), the accuracy of the analysis performed on calibrated and uncalibrated data will differ, but probably not so fundamentally as to adversely affect the analysis results and subsequent forestry measures. In the case of data acquisition by two different sensors (RGB and NIR) separately, calibration of the scanned UAV data is absolutely necessary.

If calibration targets with known spectral reflectance were not used when acquiring UAV data, or a UAV platform (camera) without a sensor measuring solar irradiance was used, it is not possible to calibrate data within photogrammetric processing (in software listed in chapter Acquired data processing). This deficiency can be partially remedied by two methods: (a) by measuring the real spectral reflectance using a spectrometer, both in the field using field spectrometers and on samples taken in the laboratory (Albrechtová et al., 2017). If in such a case the spectral reflectance is not measured directly at the time of the UAV raid, it is desirable to focus primarily on surfaces that are spectrally stable (constant) during the year. Such spectral data can be used directly to calibrate UAV images and achieve very accurate calibration. (b) empirically using calibration algorithms based on image normalization, for example by linear regression of the spectral bands. Again, it is necessary to find such surfaces in the image that are constant within the season and the electromagnetic spectrum. Suitable calibration algorithms (for example, so-called Flat Field corrections and others (Harris, 2018)) are available in most software focused on remote sensing data processing. With this solution we achieve rough values of spectral reflectance, for accurate detection we recommend primarily the use of calibration targets. Nevertheless, this method of calibration can be applied in extreme cases using two different sensors (for example RGB and modified NIR) and the results of detection of the spruce bark beetle infestation will be more reliable than when using images without calibration.

2.3.2 Determination of vegetation height (nDMP)

An important input for the detection of the spruce bark beetle infestation, specifically for the delimitation of the tops and crowns of individual trees, are height data calculated by initial photogrammetric processing (PART A) and a digital model representing vegetation height derived from them (normalized digital surface model; nDSM). Vegetation height can be easily obtained from UAV data by subtracting the digital terrain model (DTM) from the digital surface model (DSM), see Fig. 3.4. The calculation can be performed in any GIS or remote sensing software.

Figure 3.4: Calculation of normalized vegetation height from UAV data, where nDSM = normalized digital surface model; DSM = digital surface model; DTM = digital terrain model; and its demonstration

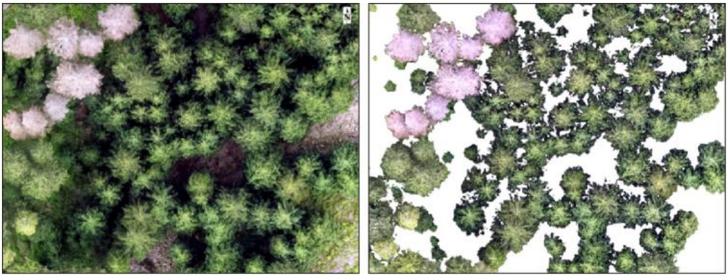
Source: own

Since passive UAV sensors (RGB, multispectral, hyperspectral cameras) measure only the reflected electromagnetic radiation from the treetops, it is often problematic to obtain accurate information about the altitude of the terrain (DTM) in dense vegetation. For the photogrammetric calculation of the terrain, it is essential that the terrain is visible in the images, which is practically impossible in the involved forest stands. In such cases, the UAV DTM can be replaced by other data inputs based on active remote sensing sensors. The currently most suitable generally available solution for the Czech Republic is to use the Digital Terrain Model of the Czech Republic of the 5th generation (DMR 5G). This digital model was created based on data obtained by aerial laser scanning and is distributed for a fee by the Czech Office for Surveying, Mapping and Cadastre (ČÚZK) for the entire territory of the Czech Republic. All information about the dataset can be found on the ČÚZK[2] website, the budget for the purchase of DMR 5G sheets is part of Chapter 6.

Elimination of shadows

Another methodological step is the unmasking of shadows, which is important for obtaining homogeneous (pure) pixels preferred both in the calculation of selected predictors (spectral indices) of bark beetle attack, and for possible (un)controlled classification based on raw (original) spectral bands taken by UAV sensors. An example before and after unmasking shadows from a UAV image is shown in Fig. 3.5.

Figure 3.5: A section comparing the UAV image before and after unmasking shadows and low vegetation



Source: own

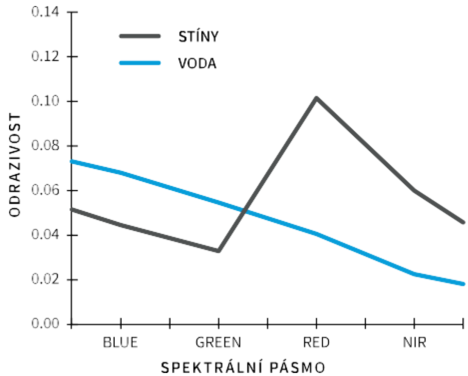
In order to obtain the most reliable results, it is more advantageous to prevent the presence of shadows already during the acquisition of UAV data, i.e. to acquire unshaded scenes according to the recommendations given in PART A of the methodology.

If the acquired data still contains shadows, it can be effectively unmasked using the RED or NIR spectral band, using an approach called thresholding. Thresholding is based on finding a threshold value in our case distinguishing unshaded and shaded parts of tree crowns. In addition to thresholding, it is possible to use more advanced methods based on (un)controlled classification. Both approaches assume that the value of the spectral reflectance of shadows in both RED and NIR approaches 0 and thus differs significantly from other objects in the image (see Fig. 3.6).

Figure 3.6: Average spectral curve of shadows (gray) and its comparison with

selected very spectrally similar types of land cover (water - blue)

Source: Malahlela, O.E., 2016. Inland waterbody mapping: towards improving discrimination and



extraction of inland surface water features. IJRS. 37 (modified)

However, this assumption does not fully apply to water bodies, the spectral reflectance of which may in some cases resemble the reflectivity of shadows. In some cases, water areas can be included in the shadow category during detection. However, water bodies are irrelevant to the occurrence of the spruce bark beetle and their confusion is thus irrelevant. More information can be found in both Czech (Voluntary, 1998) and foreign language (Lillesand et al., 2015) literature summarizing not only the general issues of remote sensing of the Earth.

Recommendations for PART B - Preprocessing of UAV data

In tab. 3.4 we present a list of recommended software and tools that will lead to the creation of appropriate outputs necessary for the next part of processing. These tools were used in our study.

Table 3.4: Recommended parameters for the Preprocessing of UAV data

Creating a multilayer file	
Software	Harris ENVI / ESRI ArcGIS
Tool	Layer Stacking / Composite Bands
Radiometric calibration	
Software	Harris ENVI
Tool	Flat Field AtmosphericCorrection
Determination of nDMP	
Software	Harris ENVI / ESRI ArcGIS
Tool	Band Math / Raster Calculator
Elimination of shadows	
Software	Harris ENVI
Tool	Image thresholding

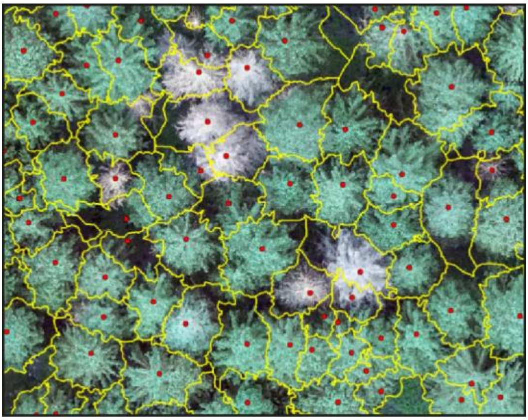
Source: own

3.3 PART C: Detection of (un) infested trees

Delimitation of treetops

A normalized digital surface model (nDSM) is used as input data for the delimitation of treetops.[1] The first step of delimitation is to unmask locations with trees higher than 15 m. This step assumes that the spruce bark beetle attacks (prefers) primarily spruce stand older than 60 years, which is usually higher than 15 m. The normalized digital surface model must be further filtered using a low-frequency filter (for example, the Filter tool in ArcGIS, etc.). Filtering is important to eliminate the possible detection of multiple treetops on a single tree crown, which is very common due to the detailed resolution of UAV data.

Figure 3.7: Example of automated delimitation of treetops and crowns based on a normalized digital surface model (nDSM).



Source: own

The definition of treetops can be effectively performed by the tools of focal statistics (Focal Statistics), which are available in any geographic information system. The size of the floating window (so-called kernel) of the focal statistics should be chosen concerning the maximum

[1] *Optionally, crowns of individual trees can be delimited based on the tops using the inverted Watershed algorithm (Panagiotidis et al., 2017) or an alternative approach based on object classification (Komárek et al., 2018) over a mosaic of UAV images. The step of delimiting tree crowns does not have a significant effect on the accuracy of detection, but it can be a suitable basis for presentation (Fig. 3.7).*

size of the treetops in the locality of interest. If a smaller floating window size is selected, the algorithm will detect multiple tops on one tree crown and vice versa. To achieve the maximum accuracy of delimitation, it is advisable to perform its visual inspection and, if any defects are found, to manually erase the excess treetops.

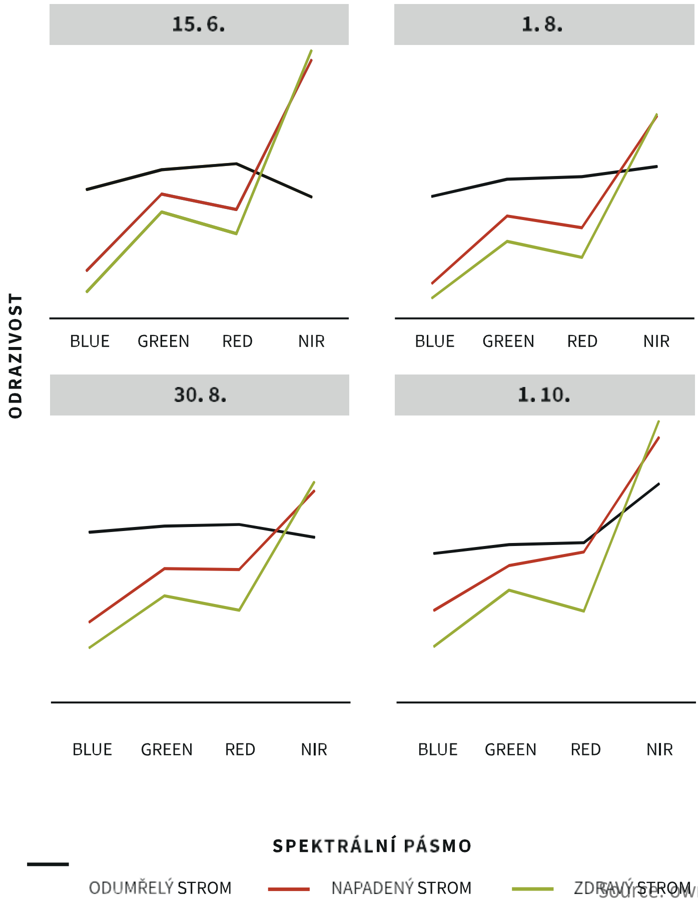
Calculation of attack predictors

Since the attack of the spruce bark beetle is first and foremost reflected on the top of the infested trees, it is advisable to create a 0.5 m buffer zone around each of the detected treetops and in each zone calculate the average value of the selected predictor (spectral index, reflectivity of the raw (original) bands, etc.) using zonal statistics tools (e.g., Zonal Statistics in ArcGIS). The detection of infested trees is then based on the assumption that after infestation, the tree changes its spectral reflectance, which is affected by sensors placed on the UAV carrier, especially in the NIR part of the electromagnetic spectrum (see Fig. 3.8).

Tree classification – coniferous vs. deciduous

If the area of interest of the analysis is not formed by a continuous spruce monoculture and there is also a higher percentage of deciduous individuals (mixed forest stand), we recommend unmasking them from the multispectral mosaic of UAV images to achieve maximum acceptability. From our point of view, the most suitable solution is the use of controlled “object” classification (for example in ArcGIS or ENVI software), where we use the above calculated average values of spectral reflectance of individual channels (B, G, R, NIR, etc.) as input objects of classification in 0.5 m buffer zones. Thanks to the detailed resolution of UAV data, field measurements are not required for classification, but it is possible to subtract training data (to distinguish coniferous vs. deciduous tree) for both groups of trees directly above the UAV image. The difference in the spectral behaviour of the average coniferous and deciduous tree is shown in Fig. 3.9. On the other hand, deciduous trees will in most cases behave like healthy (coniferous) trees on multispectral mosaics, and so the algorithms (approaches) described below should detect them. Therefore, we classify this step of the methodology as optional.

Figure 3.8: Demonstration of the change in the average spectral reflectance of helthy, infected, and dead trees within one generation of the spruce bark beetle.



Source: own

Detection of infested trees

Based on the knowledge and experience of users of the methodology in the field of remote sensing, specifically related to the techniques of processing (multi) spectral images, several methodological solutions for the detection of infested trees can be recommended. The individual solutions differ in the level of requirements for processing know-how, the need for field measurements, the number of input (multi) spectral mosaics, and thus the assumed reliability of the achieved results. Detection of infested trees can be successfully addressed by (a) thresholding above a pre-calculated vegetation index; (b) a decision tree; (c) uncontrolled classifications of raw (original) multispectral images; and (d) controlled classifications of raw multispectral images. The above approaches can further be applied either (i) to a single UAV image or a vegetation index calculated from it; (ii) the difference between the two vegetation indices calculated from images taken before and after the period of the spruce bark beetle; (iii) a pair of raw images; (iv) on a merged pair of raw images, etc. Detection should in all cases be based on an object classification approach, which, unlike the pixel approach, eliminates the identification of the part of the crown as infested and part as healthy (so-called "salt and pepper" effect). The methodology of detection of infested trees aims to find sufficiently accurate and at the same time user-friendly and processing-friendly detection approaches. Such approaches are the thresholding of vegetation indices and the technique using decision trees. On the contrary, this is the case for detection approaches based on uncontrolled and controlled classification, which often achieve slightly higher accuracy, but when their user intensity is not suitable for practical use, and therefore we will not elaborate further on the methodology.

Table 3.5: Properties of selected processing methods for individual detection of infested trees by the spruce bark beetle; resolution by a range of symbols -, more symbols mean higher/larger requirements/suitability.

	Thresholding	Decision Tree
Software requirements	-	-
Number of UAV images	-	- -
Processing time	-	- -
Requirements for know-how	-	- - -
Credibility of results	- -	- - -

Source: own

For practical use, it is recommended to use a technique based on the analysis of two images using a decision tree, which can be transferred to any UAV data or areas of interest without major problems. Decision tree detection assumes that there is a significant difference in the red (R) and near-infrared (NIR) portions of the electromagnetic spectrum on a pair of images (see Figure 3.8 on page 38). If the user of the methodology cannot take a pair of pictures, then we recommend using the method of thresholding the vegetation index (for example, NDVI) calculated from a single frame. The differences between the two methods are comprehensively summarized in Tab. 3.5. The above-calculated (chapter Calculation of infestation predictors) average values of vegetation index/spectral channels in 0.5 m buffer zones around the detected treetops serve as input data for the detection of trees infested with the spruce bark beetle.

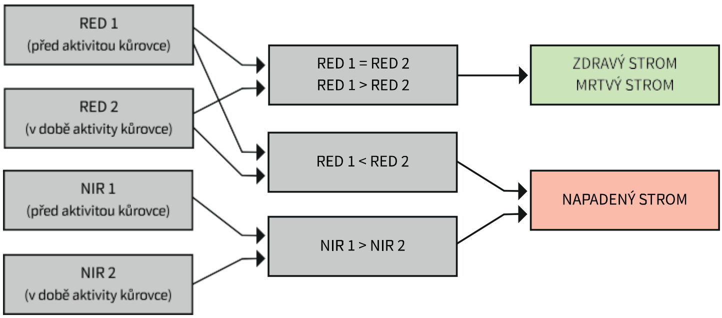
A) Decision tree technique over double frames

The principle of detection using Decision Tree, i.e., the difference between a healthy and an infested tree, consists of detecting trees in which there was an increase in reflectivity in the red (R) part of the spectrum and at the same time a decrease in reflectivity in the near-infrared (NIR) spectrum. It is, therefore, necessary to take a set of pictures from two different periods to decide. It is ideal to take the first picture of the stand before the activity of the spruce bark beetle. The second image according to habitat and climatic conditions should then be taken a few weeks after the start of its activity (see paragraph 3.1 on page 26). The decision tree itself can be created with common GIS tools using the conditional function. In both images, it is necessary to read the values of trees in the R and NIR bands. Subsequently, for example, using the Con function in ArcGIS, determine a condition that distinguishes an infected tree from a healthy/dead one, see Fig. 3.10.

By using the conditional function to distinguish the health of the tree, we achieve a binary result (raster), i.e. the answer to the question "Is the tree infected?" yes, no. To clarify this decision, the probability of classifying a tree in the relevant category can be calculated. Using a suitable GIS function (for example, Class Probability in ArcGIS software), the percentage probability of its correct classification can be calculated for each tree. The limit of sufficient probability for determining the infested trees is then on the user of the methodology. If a higher threshold value (e.g. > 80%) is set, not all infested trees may be detected, on the contrary, if a lower value (e.g. > 60%) is set, the number of infested trees will be overestimated and all infested trees will be detected in the results, uninfested individuals with a significantly deteriorated health (with a very similar spectral reflectivity) should also be considered infested trees. On the other hand, this information can be used later, because these trees can become an easy target for future generations of the spruce bark beetle due to their deteriorating health. The results of the detection can therefore be easily adapted to the interests of the user of the methodology, i.e. slightly above or underestimated the number of infested trees. Within the methodology, we always recommend overestimating the number of infested trees in the detection process and to make decisions only based on the calculated probability of inclusion in the class of infested trees.

In addition to the R and NIR bands, it is possible to include other bands available in the multispectral mosaic, such as G and B, in the decision tree. Comparisons of spectral reflectivity for an infested and healthy tree are summarized in their study by Abdullah et al. (2018). However, when using all spectral bands, we can often lose infested trees in the results, which show the initial signs of infestation and their spectral reflectivity is between the infested tree and the uninfested tree with deteriorating health. On the other hand, we only get infested trees with a high probability. The use of all available spectral channels thus again depends on the needs of the user of the methodology.

Figure 3.10: Demonstration of a detection method based on the decision tree method using selected spectral channels (R, NIR) from two input UAV images



B) Vegetation index thresholding

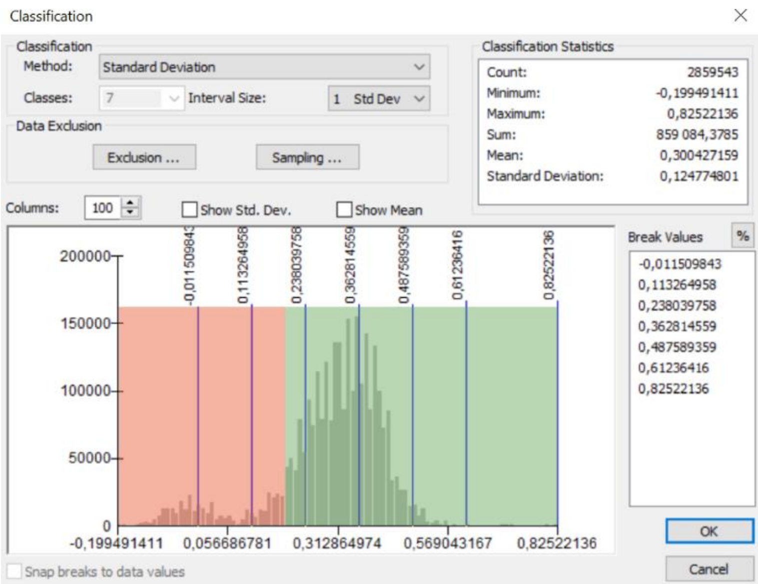
Thresholding is based on finding a threshold value that distinguishes infested trees from healthy trees. Thresholding can be performed manually, i.e. manually find the desired value, or automatically using implemented algorithms (such as Standard Deviation, Natural Breaks - Jenks, etc.) in any GIS or remote sensing software.[2] Threshold detection is always performed on single-channel inputs, which are most often vegetation indices. The usability of vegetation indices for the detection of spruce bark beetle infestations has already been verified in their work (Heurich et al., 2010; Minařík & Langhammer, 2016). The method excels in its simplicity and easy interpretation. However, in variable areas of interest, it can achieve less accurate/credible results than a decision tree-based approach. If the threshold is chosen

[2] In addition to the Standard Deviation algorithm, it is also possible to use the Natural Breaks (Jenks) algorithm with two intervals to automatically determine the threshold value in localities with a large number of already dead trees, i.e. old spruce bark beetle foci. The interval with lower values of vegetation index then represents infested trees, the interval with higher values of healthy trees.

inappropriately, the approach overestimates or, on the contrary, underestimates the number of (un)infested trees.

For a practical (semi-) automatic threshold search, the recommend the use of an approach based on the calculation of the standard deviation (Standard Deviation). Depending on the number of dead trees (dry trees infested with the spruce bark beetle in previous generations), the infested trees are located in the first two to three intervals calculated from the left part of the histogram (see Fig. 3.11). The figure shows a bimodal (two-peak) distribution of NDVI vegetation index values, where the values around the first (lower) peak represent dead trees (1st – 2nd standard deviation interval), values around the second (higher) peak healthy trees (4th - 7th interval) and the area between them (3rd interval) newly infested trees. Subsequently, it is necessary to reclassify the values of the vegetation index into the appropriate categories (for example, the Reclassify tool in ArcGIS). As for results based on the decision tree method, it is possible to calculate the probability of correct classification of trees into a given class in the same way.

Figure 3.11: Demonstration of a detection method based on thresholding of vegetation indices; the data divided into seven clusters symbolize the distinction between healthy (green) and infested (red) trees; an example of using ArcGIS software



Source: own

C) Calculation of vegetation indices

Vegetation indices form an extensive subcategory of so-called spectral indices. The list of recommended vegetation indices for the detection of infestation of forest stands by the spruce bark beetle, together with the computational equations, is presented in Tab. 3.6. Vegetation indices are most often based on information from sensors sensing at four intervals of the electromagnetic spectrum (i) blue radiation 400–500 nm, (ii) green 500–600 nm, (iii) red 600–760 nm, (iv) near-infrared 760– 1400 nm. In the case of professional cameras with a higher spectral resolution, it is also possible to apply vegetation indices using other parts of the electromagnetic spectrum. You can find a list of them, for example, with the help of the ENVI3 software. Vegetation indices in a tab. 3.6 were applied and tested at the selected locality and all achieved very similar results in the detection of infested trees and are thus interchangeable. It isbecause of the fact that most vegetation indices based on the same spectral bands correlate with each other (Klouček et al., 2018). In the case of connection of other spectral bands in addition to those mentioned above, indices working with the Red Edge band (700– 750 nm) can also be recommended (Minařík & Langhammer, 2016). Within the methodology, a standardized differential vegetation index (NDVI) can be recommended as a suitable vegetation index, which represents a compromise between the complexity of the calculation, interpretability of the achieved results and is also an experienced indicator of vegetation health outside the remote sensing community.

Table 3.6: List of potentially usable vegetation indices for early detection of infested forests with spruce lichen-eater; GREEN, RED and NIR represent the respective spectral bands of the UAV data

Vegetation index	Formula
Greenness Index	tt $=\frac{GREEN}{RED}$
Green Ratio Vegetation Index	tt $=\frac{NIR}{GREEN}$
Normalized Difference Vegetation Index	D $=\frac{NIR-RED}{NIR+RED}$

Source: Minařík, R., Langhammer, J., 2016. Use of a multispectral UAV photogrammetry for detection and tracking of forest disturbance dynamics. Int. Sheet. Photogram. ISPRS. 41 (modified)

3 *https://www.harrisgeospatial.com/docs/using_envi_Home.html*

D) Distance from the nearest infested tree

Based on expert estimation, the critical distance for tree infestation by one generation was determined. This distance serves within the methodology for the final elimination of remote trees, which are similar in their spectral properties, due to, for example, reduced health due to drought, etc., to individuals affected by the bark beetle. The critical distance for infestation was set at 50 m from the nearest infested tree, which can be both a standing individual and a tree-eaten but previously harvested tree.[4] This distance depends on several climatic, topographic, and other factors, and therefore it is appropriate when choosing it, always proceed consider the conditions of the locality of interest and consider the degree of its infestation by the bark beetle. Therefore, within the methodology, we assume that if the tree is located far enough away from the outbreak in an otherwise healthy forest stand, the probability of infestation by the bark beetle is very low, and therefore we recommend considering it as an uninfested individual. For example, the Near function in ArcGIS software can be used to calculate the distance.

The distance of the infested tree from the outbreak (infested/ dead/felled trees during the last swarm) can be used to recalculate the probability of classifying the tree as an infested tree. The probability of attack will thus decrease with increasing distance of the tree from the focus (probability of attack at a distance of 0 m = 100%, on the contrary, the probability of attack at a distance greater than 50 m = 0%). The resulting probability is then obtained by multiplying the probability of correct classification into the class of the infested tree with the probability based on the distance from the focus of the infestation.

[4] The threshold value for the maximum spreading distance of the bark beetle should be based on the specific experience of the forest manager, climatic and topographical factors. The value of 50 m specified in the methodology is not binding. In ideal conditions for the spread of the bark beetle, it can reach hundreds of meters.

Creation of a database and map outputs

The practical output of the methodology is a database representing the position (x, y, z) of treetops with information on the status of the bark beetle infestation (healthy vs. infested tree). To visualize the achieved results, it is possible to use either classified wrapping zones (buffers) or their connection with treetops (for example, using Extract Values to Points in ArcGIS). To obtain a seamless map, it is also possible to connect classified wrapping zones (buffers around the tops of trees or the tops themselves) to their defined crowns with overlay tools (for example, Overlay in ArcGIS) in GIS.

Software requirements

Within the software requirements for the second part of the methodology focused on UAV image processing (PARTS B and C), it is possible to use both commercial (e.g. Harris ENVI, PCI Geomatics, ERDAS IMAGINE, ESRI ArcGIS, etc.) and freely available solutions for most steps. (SNAP, QGIS, R, and others). The software does not differ much (except for R) and with their use, comparable results can be achieved. The use of R presupposes advanced user knowledge of scripting. Before using any software, we always recommend that you first study its user manual in detail, with emphasis on the recommended parameters of the tools used.

Recommendations for PART C – Detection of (un)infested trees

In tab. 3.7 on the next page, we present a list of recommended software and tools that will lead to the creation of the corresponding final outputs.

3.4 PART D: Summary scheme and specific example of dataprocessing

Below is a specific example of the application of the proposed methodological procedure in a selected locality of interest, together with a summary scheme leading to the described results. The locality of interest consists mainly of a spruce culture with foci of bark beetle. The onset of bark beetle activity occurred at the end of June, and in August it was already possible to detect newly infested trees based on the methods and procedures described above. A total of four UAV air raids were performed at the mentioned locality using RGB (ordinary digital camera) and modified NIR cameras, on which all detection approaches mentioned in the methodology were tested. ESRI ArcGIS software was used for pre-processing of UAV data and self-detection of infected trees.

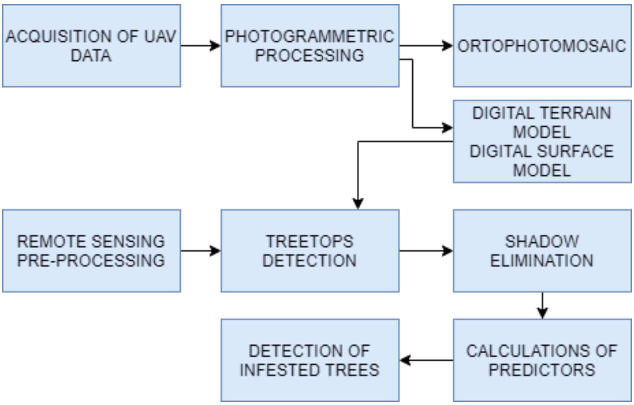
Table 3.7: Recommended parameters for the UAV Data Processing section

Delimitation of treetops		
Software	ESRI ArcGIS	
Tool	Focal statistics	
Calculation of predictors		
Software	ESRI ArcGIS	
Tool	Zonal statistics	
Detection of infested trees	One image	Pair of images
Software	ESRI ArcGIS / Harris ENVI	ESRI ArcGIS / Harris ENVI
Tool	ESRI ArcGIS/Harris ENVI Thresholding	ESRI ArcGIS / Harris ENVI Decision tree

Source: own

The individual steps reflect the methodological procedure described above. The data acquired by the unmanned aerial vehicle were photogrammetrically processed in the form of orthomosaic, digital surface model, and digital terrain model. The digital surface model was normalized by a digital terrain model and smoothed to a low frequency. Focal statistics defined the treetops above a normalized digital surface model, and a 0.5 m buffer zone was created around trees higher than 15 m. The orthomosaics were combined into a multilayer set and radiometrically calibrated. Unwanted shadows were unmasked from the combined orthomosaic by thresholding the NIR channel. The standardized differential vegetation index (NDVI) was calculated from the respective spectral channels. Subsequently, the average values of the attack predictors (NDVI for thresholding, spectral reflectance of the R and NIR channels for the decision tree) were read in the buffer zones using zonal statistics. The actual detection of infested trees was performed by the decision tree method over a pair of images and by the NDVI thresholding method of one image. The individual methodological steps are schematically shown in the diagram below (Fig. 3.12).

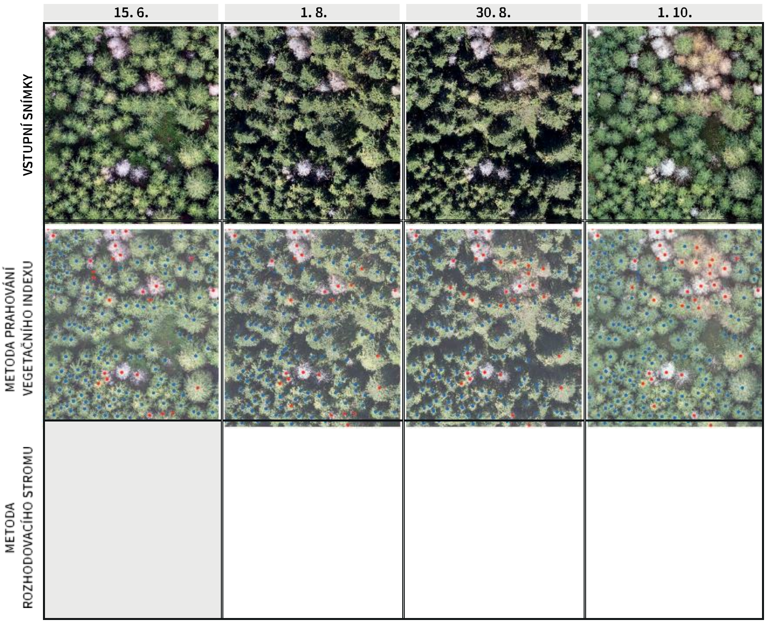
Figure 3.12: Scheme of process steps leading to the detection of infested trees



Source: own

The result of the presented methodology is a database of bark beetle (un)infested trees, supplemented by the probability of correct classification into the relevant category and the distance from the outbreak. In the example in Fig. 3.13, the results of individual detection approaches are presented based on four input orthomosics, whereby blue points uninfested trees are shown and infested by red. In the case of the threshold-based approach, dead trees are also detected within the category of infested trees. For the decision tree, the created algorithm is sensitive only to newly attacked individuals, however, if necessary, it is possible to simply add additional decision branches and thus distinguish dead trees infected in previous generations. The picture also shows that the number of infested trees detected by each approach increases with the current season (the first image taken on 15 June captures the area of interest just before the activity, images were taken on 1 and 30 August during the activity and the image was taken 1. Octoboer after the activity of the bark beetle).

Figure 3.13: Comparison of detection methods



To demonstrate the usability of the mentioned detection approaches, the tab. 3.8 shows their accuracy calculated based on 50 validation (reference) samples (41 healthy, 9 infested trees) from 200 available. It is clear from the table that the accuracy of detection in both cases increases with the time since the tree was attacked by the bark beetle. Using a decision tree, slightly higher accuracy can be achieved than in the case of thresholding. In the first two images, the infested trees are practically indistinguishable from the uninfested ones, on the contrary, in the remaining two they are already clearly distinguishable. Both the overall detection accuracy (78–94% in the case of thresholding vs. 82–96% in the decision tree) and the user (UA = 0–75% vs. 50–90%) and processing (PA = 0–100% vs 11– 100%) accuracy for the category of infested trees. The results show that the appropriate time for taking images in the case of our sample data obtained by a modified NIR camera ranges from 1 to 30. August. However, using professional multispectral cameras, we can assume that it will be possible to detect infested trees even earlier. It is also beneficial for forest management to include in the decision-making process data on the probability of including a tree in the category of infested tree. The presented example clearly demonstrates the usability of the translated methodology for the detection of trees infested with lichen-eating.

Table 3.8: Accuracy of detection of infested trees by bark beetle using decision tree and thresholding where 0 = uninfested trees, 1 = infested trees, UA = user accuracy, PA = processing accuracy

	15. 6.	**1. 8.**	**30. 8.**	**1. 10.**
Vegetation index thresholding method				
U_{A0} [%]	0,81	0,85	0,95	1,00
U_{A1} [%]	0,00	0,50	0,70	0,75
P_{A0} [%]	0,95	0,95	0,93	0,93
P_{A1} [%]	0,00	0,22	0,78	1,00
Overall accuracy [%]	**0,78**	**0,82**	**0,90**	**0,94**
Decision tree method				
U_{A0} [%]	–	0,83	0,97	1,00
U_{A1} [%]	–	0,50	0,73	0,90
P_{A0} [%]	–	0,98	0,93	0,98
P_{A1} [%]	–	0,11	0,89	1,00
Overall accuracy [%]	**–**	**0,82**	**0,92**	**0,98**

Source: own

4 Evaluation of the novelty of the submitted procedures

The project is a typical interdisciplinary study linking GIS, remote sensing, and animal ecology. It brings a new unique and at the same time effective solution for monitoring the spread of insect pests in forest ecosystems on the example of the spruce bark beetle. The main benefit is the use and application of modern approaches and technologies in the form of unmanned aerial vehicles, the advantages of which are in particular (a) extremely high spatial resolution, which is particularly valuable for local detection at the level of specific trees; (b) an optional time resolution that allows data to be acquired at the key time required for effective detection, unlike other platforms regardless of, for example, cloud cover, etc.

Across the literature, studies can be found to detect and spread the bark beetle using remote sensing methods (Senf et al., 2015), using conventional digital cameras and professional multispectral ones (Meddens et al., 2013; Latifi et al., 2014a, b; Senf et al., 2015; Hais et al., 2016), or hyperspectral sensors (Lausch et al., 2013; Fassnacht et al., 2014) placed on satellites or unmanned aerial vehicles (Näsi et al., 2015; Minařík & Langhammer, 2016; Brovkina et al., 2018; Marina et al., 2018) or aircraft carriers (Bright et al., 2013, 2014). The research published so far represents case studies, mainly in the field of unmanned aerial vehicles, proving the applicability of Earth remote sensing methods for the detection of trees infested with spruce bark beetle, which have not yet come up with a comprehensive practical solution. To the best of our knowledge and belief, there is no such comprehensive methodological approach yet. Current research has not yet provided an answer to the question of when the site should be scanned for the detection to be sufficiently effective and timely. From our research it is possible, depending on the nature and conditions of the locality of interest, to distinguish a healthy and infected tree about 3-6 weeks from infestation. Therefore, the detection of early stages of bark beetle infection is still a current and future research challenge, especially with the use of newly available (un)professional platforms and sensors, which can further refine the detection process and at the same time make it possible to detect an infected tree in its earlier stages. Although the proposed methodological procedure represents a sufficiently accurate and effective solution for the detection of infested trees with bark beetle, it still has its reserves, especially in distinguishing the early stages of infested trees from trees not infested with significantly worsened health. However, it is very likely that thanks to the current rapid technological development in the field of advanced image processing methods, unmanned aerial vehicles, and sensor miniaturization, the results of which can be easily implemented in the presented methodology, it will be possible to eliminate this single shortcoming. On the other hand, this shortcoming is not an obstacle to the practical implementation of the methodology, because yet uninfested trees with deteriorating health located near the outbreak of bark beetle are likely to be attacked by future generations, and therefore their possible extraction can be considered an acceptable preventive measure. The methodology is transferable applicable in the study of other biotic disturbances in other ecosystems. The acquired knowledge about the spread of the bark beetle is not only of environmental significance but can be the basis for preventive modelling of the spread, which can prevent possible economic damage. The activity of the bark beetle in forest stands not only in the Czech Republic is a serious problem today, which is why it is a very actual topic.

.

5 Description of the application of the methodology

The methodology of spruce bark beetle detection is intended mainly for forest owners and managers. It can therefore be used wherever timely and fast action leading to efficient forest management is needed. The developed methodological procedure has an interdisciplinary character connecting knowledge from the field of ecology of the spruce bark beetle, data collection using unmanned aerial vehicles, processing, and analysis of the spectral image. Detailed processing of the description of the methodological procedure enables the creation of a user-friendly application. The methodology is applied by The Krkonoše Mountains National Park Administration for the detection of spruce bark beetle infestation within the non-intervention zones of the national park. The methodological procedures are not limited to use only for the territory of the Czech Republic, but are transnationally transferable, and thus practically applicable in other parts not only of Central Europe. The described methodological steps are also transferable for the detection of other biotic pests not only in forest ecosystems. In addition to practical applications, the methodology can serve as a guide for other applications of remote sensing of the Earth or can be used as study material, both for ecological and forestry study fields, as well as for GIS and remote sensing.

Within the TACR ZETA project No. TJ01000428: Detection of infection forest bark beetle (Ips typographus) in advance using unmanned air vehicles, the proposed methodology will be used as a basis for the creation of follow-up user-friendly software by HSI, spol. s r.o.

6 Economical aspects

The methodical method of detecting the infestation of the forest by the spruce bark beetle is a tool that allows forest managers to decide on the method and extent of harvesting the infested wood mass before the next, often even geometric spread of the spruce bark beetle to the surrounding stands. If the infested trees are not quickly harvested and rehabilitated, this condition can lead to the destruction of the forest. Thanks to this methodical detection procedure, it is possible to prevent this unwanted phenomenon. Proper detection of infested trees based on multispectral image processing has direct economic implications. The current state of harvesting of individual trees near the outbreak is set in such a way that often healthy trees are also harvested together with the infested trees. However, any unnecessarily harvested healthy tree increases financial (and environmental) damage and increases the cost of remediation.

Based on market research, the current price of logging ranges from 150 to 900 CZK/m3. However, the price is not fixed, it depends on the mined weight, vertical terrain, or approach distance. The price of mining on flat localities is lower than the price on a slope. Likewise, the resulting amount is affected by the distance of the landfill from the place of extraction and is also based on the need to use specialized mechanization (forest lifts, walking harvesters, or pulling by horses). As difficult as evaluating the cost of harvesting, the calculation of the total extent of forest matter in the stand is. The extent depends on the age of the forest. Spruce 80 years old can have 400 to 500 m3 of wood mass per hectare, the price of harvesting one hectare is based on 150 to 300 CZK. A common phenomenon in the harvesting of infested timber is the felling of surrounding healthy trees to reduce the risk of the felled tree not being felled. If we consider a circular outbreak of infested trees with an area of 0.5 ha, including the surrounding 50-meter zone from the last infested tree, the total area of the harvested site is 2 ha, which is four times more. For correct detection, the site must be flown by an unmanned vehicle with a corresponding sensor. The cost of flying the site with an unmanned area vehicle with an area of 1 to 10 ha with a multispectral camera is 15 to 30 thousand CZK. This price includes a ground survey of the fitting points with a geodetic instrument and processing of the acquired images into an orthomosaic. If it is necessary to use ready-made digital terrain or surface models, which are provided, for example, by ČÚZK, it is necessary to add to the amount of approximately CZK 30 per 1 km2 of the monitored locality area. Although the calculation does not include the use/purchase in the methodology of recommended commercial software, which can in most cases be replaced by a suitable open-source variant, this amount is very low compared to the possible damage caused by the harvesting of healthy trees.

The current financial aspects were focused on a specific commercial forest. The following lines evaluate the bark beetle issue from a more global perspective. The current climatic conditions, the technical and economic condition of forests, and their management have most likely resulted in the greatest bark beetle calamity in modern history, not only in the Czech Republic. Area logging reveals vast areas of bare soil. The immediate interruption of the cooling and cleaning function of the forest has adverse effects on the surroundings. All these negative impacts of the bark beetle calamity will lead to a change in the environment in various parts of Bohemia, Moravia, and Silesia. If we do not try to mitigate the consequences of the bark beetle calamity by all available means, the damage to the landscape will be incalculable. The presented methodology has a great potential to detect infested trees and thus prevent/slow down the spread of bark beetles. Therefore, from our point of view, it pays to invest in the acquisition of multispectral data and to detect potentially infected localities using the created methodological procedure, even though only a part of the forest stand could be saved.

7 List of used literature

ABDULLAH, H. et al., 2018. European spruce bark beetle (Ips typographus, L.) green attack affects foliar reflectance and biochemical properties. International Journal of Applied Earth Observation and Geoinformation. 64, s. 199–209. ISSN 0303-2434. Dostupné z: https://doi.org/10.1016/j.jag.2017.09.009.

ALBRECHTOVÁ, J. et al. 2017, Metody hodnocení fyziologického stavu smrkových porostů. Česká geografická společnost, 1. edition. ISBN 978-80-905642-9-9.

BANNARI, A. et al., 1995. A review of vegetation indices. Remote Sensing Reviews. 13, 1, s. 95–120. ISSN 0275-7257. Dostupné z: http://dx.doi.org/10.1080/02757259509532298.

BRIGHT, B. C. et al., 2013. Predicting live and dead tree basal area of bark beetle affected forests from discrete-return lidar. Canadian Journal of Remote Sensing. 39, SUPPL.1, s. 37–41. ISSN 07038992. Dostupné z: https://doi.org/10.5589/m13-027.

BRIGHT, B. C. et al., 2014. Landsat time series and lidar as predictors of live and dead basal area across five bark beetle-affected forests. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 7, 8, s. 3440–3452. ISSN 2151-1535. Dostupné z: https://doi.org/10.1109/JSTARS.2014.2346955.

BROVKINA, O. et al., 2018. Unmanned aerial vehicles (UAV) for assessment of qualitative classification of Norway spruce in temperate forest stands. Geo-spatial Information Science. , January, s. 1–9. ISSN 1009-5020. Dostupné z: http://doi.org/10.1080/10095020.2017.1416994.

CHRISTIANSEN, E., BAKKE, A. 1988, The Spruce Bark Beetle of Eurasia. ISBN 978-1-4899-0789-9.

DOBROVOLNÝ, P. 1998, Dálkový průzkum Země Digitální zpracování obrazu. Přirodovědecká fakulta Masarykovy univerzity, Katedra geografie.

EDBURG, S. L. et al., 2012. Cascading impacts of bark beetlecaused tree mortality on coupled biogeophysical and biogeochemical processes. Frontiers in Ecology and the Environment. 10, 8, s. 416–424. ISSN 1540-9295. Dostupné z:

https://doi.org/10.1890/110173.

FASSNACHT, F. E. et al., 2014. Assessing the potential of hyperspectral imagery to map bark beetle-induced tree mortality. Remote Sensing of Environment. 140, s. 533–548. ISSN 0034-4257. Dostupné z: https://doi.org/10.1016/j.rse.2013.09.014.

HAIS, M. et al., 2016. Landsat imagery spectral trajectories-important variables for spatially predicting the risks of bark beetle disturbance. Remote Sensing. 8, 8. ISSN 2072-4292. Dostupné z: https://doi.org/10.3390/rs8080687.

HARRIS. 2018, ENVI Help. Harris Geospatial Solutions Ltd.

HEURICH, M. et al., 2010. Object-orientated image analysis for the semi-automatic detection of dead trees following a spruce bark beetle (Ips typographus) outbreak. European Journal of Forest Research. 129, 3, s. 313–324. ISSN 1612-4669. Dostupné z: https://doi.org/10.1007/s10342-009-0331-1.

JONES, H. G., VAUGHAN, R. A. 2010, Remote sensing of vegetation: principles, techniques, and applications. Oxford University Press.

KLOUČEK, T. et al., 2018. Selecting appropriate variables for detecting grassland to cropland changes using high resolution satellite data. PeerJ. 6, s. e5487. ISSN 2167-8359. Dostupné z: https://doi.org/10.7717/peerj.5487.

KOMÁREK, J., KLOUČEK, T., PROŠEK, J., 2018. The po-

tential of Unmanned Aerial Systems: A tool towards precision classification of hard-to-distinguish vegetation types? International Journal of Applied Earth Observation and Geoinformation. 71, May, s. 9–19. ISSN 0303-2434. Dostupné z: https://doi.org/10.1016/j.jag.2018.05.003.

LATIFI, H. et al., 2014b. Object-based extraction of bark beetle (Ips typographus L.) infestations using multi-date LANDSAT and SPOT satellite imagery. Progress in Physical Geography. 38, 6, s. 755–785. ISSN 0309-1333. Dostupné z: https://doi.org/10.1177/0309133314550670.

LATIFI, H. et al., 2014a. Spatial characterization of bark beetle infestations by a multidate synergy of SPOT and Landsat imagery. Environmental Monitoring and Assessment. 186, 1, s. 441–456. ISSN 0167-6369. Dostupné z:

https://doi.org/10.1007/s10661-013-3389-7.

LAUSCH, A. et al., 2013. Forecasting potential bark beetle outbreaks based on spruce forest vitality using hyperspectral remotesensing techniques at different scales. Forest Ecology and Management. 308, s. 76–89. ISSN 0378-1127. Dostupné z: https://doi.org/10.1016/j.foreco.2013.07.043.

LILLESAND, T. S., KIEFER, R. W., CHIPMAN, J. W. 2015, Remote

Sensing and Image Interpretation. John Wiley & Sons, 7 edition.

MARINA, S. et al., 2018. Potential of multispectral imag ing technology for assessment coniferous forests bit ten by a bark beetle in Central Bulgaria. Dostupné z: https://doi.org/10.1051/matecconf/201814501005.

MARINI, L. et al., 2017. Climate drivers of bark bee tle outbreak dynamics in Norway spruce forests. Ecogra phy. 40, 12, s. 1426–1435. ISSN 1600-0587. Dostupné z:

https://doi.org/10.1111/ecog.02769.

MEDDENS, A. J. H. et al., 2013. Evaluating methods to detect bark beetle-caused tree mortality using single-date and multi-date Landsat imagery. Remote Sensing of Environment. 132, s. 49–58. ISSN 0034-4257. Dostupné z: https://doi.org/10.1016/j.rse.2013.01.002.

MEIGS, G. W., KENNEDY, R. E., COHEN, W. B., 2011. A Landsat

time series approach to characterize bark beetle and defoliator impacts on tree mortality and surface fuels in conifer forests. Remote Sensing of Environment. 115, 12, s. 3707–3718. ISSN 0034-4257. Dostupné z: https://doi.org/10.1016/j.rse.2011.09.009.

MINAŘÍK, R., LANGHAMMER, J., 2016. Use of a multispectral UAV photogrammetry for detection and tracking of forest disturbance dynamics. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences ISPRS Archives. 41, s. 711–718. ISSN 1682-1750. Dostupné z: https://doi.org/10.5194/isprsarchives-XLI-B8-711-2016.

MOUDRÝ, V. et al., 2018. Comparison of a commercial and home-assembled fixed-wing UAV for terrain mapping of a postmining site under leaf-off conditions. International Journal of Remote Sensing. s. 1–18. ISSN 1366-5901. Dostupné z: https://doi.org/10.1080/01431161.2018.1516311.

MÜLLER, J. et al., 2008. The European spruce bark beetle Ips typographus in a national park: From pest to keystone species. Biodiversity and Conservation. 17, 12, s. 2979–3001. ISSN 0960-3115. Dostupné z: https://doi.org/10.1007/s10531-008-9409-1.

NÄSI, R. et al., 2015. Using UAV-based photogrammetry and hyperspectral imaging for mapping bark beetle damage at tree-level. Remote Sensing. 7, 11, s. 15467–15493. ISSN 2072-4292. Dostupné z: https://doi.org/10.3390/rs71115467.

PANAGIOTIDIS, D. et al., 2017. Determining tree height and crown diameter from high-resolution UAV imagery. International Journal of Remote Sensing. 38, 8-10, s. 2392–2410. ISSN 1366-5901. Dostupné z: https://doi.org/10.1080/01431161.2016.1264028.

RAFFA, K. F. et al., 2008. Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. BioScience. 58, 6, s. 501–517. ISSN 15253244. Dostupné z: https://doi.org/10.1641/B580607.

SEIDL, R. et al., 2017. Forest disturbances under climate change. Nature Climate Change. 7, 6, s. 395–402. ISSN 1758-678X. Dostupné z: https://doi.org/10.1038/nclimate3303.

SENF, C. et al., 2015. Characterizing spectral-temporal patterns of defoliator and bark beetle disturbances using Landsat time series. Remote Sensing of Environment. 170, s. 166–177. ISSN 0034-4257. Dostupné z: https://doi.org/10.1016/j.rse.2015.09.019.

SENF, C., SEIDL, R., HOSTERT, P., 2017. Remote sensing of forest insect disturbances: Current state and future directions. International Journal of Applied Earth Observation and Geoinformation. 60, s. 49–60. ISSN 0303-2434. Dostupné z: https://doi.org/10.1016/j.jag.2017.04.004.

SONG, C. et al., 2001. Classification and change detection using Landsat TM data: When and how to correct atmospheric effects? Remote Sensing of Environment. 75, 2, s. 230–244. ISSN 0034-4257. Dostupné z: https://doi.org/10.1016/S0034-4257(00)00169-3.

8 List of publications preceding the methodology

KOMÁREK, J. 2018. Drony: přeceňovaný fenomén, nebo nástroj pro včasnou detekci kůrovce? Lesnická práce, 9, 614–615.

KLOUČEK, T., KOMÁREK, J. 2018. Potenciál dronů pro detekci stromů napadených kůrovcem. Fórum ochrany přírody, 3, 42–43. KLOUČEK, T., KOMÁREK, J., FOGL, M., LAGNER, O. 2018. Pest

outbreaks detectability in non-intervention forest using consumergrade camera within the aerial survey. Přednáška prezentována na IX Conference of the Italian Society of Remote Sensing, Florence, Italy.

KOMÁREK, J., KLOUČEK, T., FOGL, M. 2018. Classification of plant species and analysis of their structure using Unmanned Aerial Systems. Poster prezentován na 1st UAS Workshop “UAS for mapping and monitoring”, Warsaw, Poland.

LAGNER, O., WIESNER, V. 2018. Včasná detekce napadení lesních porostů lýkožroutem smrkovým za pomocí UAV a GIS. Přednáška prezentována na Konference GIS Esri v ČR, Prague, Czech Republic.

FOGL, M., KLOUČEK, T., KOMÁREK, J., LAGNER, O., GDULOVÁ,

K. 2018. Early detection of bark beetle outbreaks using unmanned aerial vehicles. Poster prezentován na Kostelecké inspirování, Kostelec nad Černými lesy, Czech Republic.

KLOUČEK, T., KOMÁREK, J., SUROVÝ, P., HRACH, K., JANATA

P. (In review). The UAV mounted low-cost sensors towards early detection of bark beetle infestation in non-intervention forest. Current forestry reports.

9 Dedication

The methodology is the result of the research project of the Technology Agency of the Czech Republic ZETA No.TJ01000428entitled:Detection of infection forest bark beetle (*Ips typographus*) in advance using unmanned air vehicles.

Detection of forest infections using unmanned aerial vehicle

Detection of forest infections using unmanned aerial vehicle – Certified methodology

Authors: Tomáš Klouček, Jan Komárek, Ondřej Lagner, Michal Fogl, Kateřina Gdulová

Publisher: Česká zemědělská univerzita v Praze, Kamýcká 129, 165 00, Praha 6

Print: Česká zemědělská univerzita v Praze, Kamýcká 129, 165 00, Praha 6 Typesetting and graphic design: Michal Fogl

Number of pages: 66

Year of publication: 2019