Deliverable summary D4.1
Application of remote sensing to the four categories of PnPs, and potential generalisation

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°771271

1. Summary

Forests across Europe have recently been ravaged by unprecedented bark beetle outbreaks, with hundreds of thousands of hectares devastated. In particular, the Norway spruce (*Picea abies*) stand has been dramatically affected by the bark beetle *Ips typographus*, as a consequence of heavy storms and drought events. For this reason, the HOMED partners have concentrated their efforts in addressing the bark beetle problem, that could be used later as a model for other pests and pathogens.

Objectives:

Use remote sensing to quantify bark beetle damage at different spatial and time scales.

Rationale:

Macroscale approach (France and Czech Republic)

The study was divided into a test of the detection power of remote sensing (A. France) and an application of it across time (B. Czech Republic)

A. Spots of trees killed by bark beetles (infestation spots) were detected in October 2018 in NE France with the analysis of multispectral images obtained from the satellite constellation Sentinel-2, belonging to the European programme Copernicus (European Spatial Agency). The spots were nested within a forest type categorisation that included homogenous areas of forest of a size larger than 0.5 ha. A ground check of the spots was carried out at various dates by the French Forest Service and the results were shared on the map obtained from the satellite survey. Satellites images from the same area were downloaded in March 2019 and compared with those of March 2018. Three bands of the visible spectrum and one band of the near-infrared were used for the comparison, all having a resolution on the ground of 10 m. To cover the whole study area, 21 image-squares, 100x100 km each, were used. In addition, a plane flight was carried out in April 2019 at specific areas to double-check the validity of the satellite detection and for a more precise identification of the damage.

The comparison 2019-2018 allowed us to identify 4 major types of infestation spots: exploited, old, extended, and new. More than 6,000 spots were detected for a total area of 1,659 ha. The use of raw satellite data involves a large overestimation of the number of spots, which is reduced to some extent by using the infrared vegetation indexes. A stronger reduction in the number of false positives is obtained when the area threshold of 0.1 ha is introduced. The reduction of the percentage of false-positive (24%) cases is associated with an increase in the percentage of false-negative cases (28%). The balance between the two is led by the spot size and the limitation is likely associated with the resolution of the satellite image (10 m). This resolution may allow an acceptable estimation of the beetle damage at a large scale whereas it is not fully reliable for precise identification of the spots at a smaller scale, especially when the spots are small. As detection of small spots is important for the deployment of the 'early detection-rapid intervention' approach, it would be desirable to detect spots at their very beginning, i.e. when only a few trees are infested. This approach does not seem feasible with Sentinel-2 images at a large scale and a higher resolution is required.

B. The application across time of the large scale approach was carried out in NE Czech Republic over an area of more than 300,000 ha of forest. Two hundred infestation spots were identified on the basis of the map on the ground and used for testing the satellite images, i.e. Sentinel 2 images captured in May of every single year in the period 2016 – 2020. Calibration and atmospheric correction of sentinel images were performed using the SNAP (ESA) software and NDVI layers were created using ArcGIS software (ESRI). The

average value of NDVI of every single training group was calculated for every single year and compared. The range of NDVI decreases during the year when the infestation spot has appeared varies between 33 and 72%.

A total of 343,530 bark beetle spots were identified in the period 2016 – 2020. Spots covered 23,472 ha in total. Spots and covered areas are described for every specific year in Table 3. The spread of bark beetle in time follows the west direction. Elevation of bark beetle spots varied in the range between 213 and 1432 m with a mean between 400 and 700 m, where the largest spruce forest stands were located. The temporal trend showed an outbreak to reach higher altitudes due to the west direction move towards the High Jeseniky mountain range.

Mesoscale approach (Italy)

An area of interest of about 24 km^2 for which there was a history of drought events and storm damage was selected (Gares valley, Dolomites). Satellite images taken by Sentinel 2 constellation were used. To assess changes in forest health, we used a comparative approach across time-series images. First, we calculated the NDVI index for each year. Then, a difference raster was computed for each couple of years. To avoid non-forested pixels we created a mask for spruce coverage. We used satellite images taken in 2015 as an initial condition. Finally, we calculated the difference in pixel values between the following years. We set threshold values (- 0.1) on NDVI-difference outputs in order to point out NDVI-falling spots. We used ArcGIS pro for raster calculation and processing and QGIS for result visualization and map printing.

The study pointed out limitations and potential development of research. We worked only in south-facing slopes in order to avoid shadows and poorly lighted slopes. In following surveys, topographic correction should be considered as a pre-processing step. We found no difference in values of vegetation indices between windthrows and bark-beetle-killed trees, based on ground observations. Currently, our remote sensing approach is not able to disentangle between wind and bark beetle damage. Field surveys or high-resolution aerial photography are still important tools for remote sensing calibration and assessment. Finally, spatially explicit databases are opening new perspectives in understanding dynamics and interaction with climatic and abiotic variables, even more important under a climate change perspective.

Microscale approach (Czech Republic)

With the aim of identifying infested trees still green, in 2019 surveillance of bark beetle using Unmanned Aerial Vehicle (UAV) has been carried out in two selected forest stands in the South-Moravian region in the Czech Republic in an area of 420 ha. The survey was carried out using UAV with a multispectral camera. To identify the position of every single tree data processing was carried out in the following steps: 3D point cloud was created using the photogrammetry of overlapping images captured in green, red and red edge bands.

Aerial data provide highly accurate outputs to identify infected and dead trees attacked by the bark beetle. Results describe the reliability of detection of the European spruce bark beetle attack using UAV in the range of 94% - 97% in case of dead trees and 78% - 85% in case of damaged (still green) trees.

Teams involved:

UNIPD – coordination and application in Italy

MEND – application in the Czech Republic

TPZF – application in France

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2. Introduction

Forests across Europe have recently been ravaged by unprecedented bark beetle outbreaks, with hundreds of thousands of hectares devastated. These insects are widespread and numerous in species and have generally played an important part in forest ecology. However, warmer temperatures, increased spread of disease and heightened drought stress are accelerating this epidemic and causing potentially irreversible chase. For example, in the Czech Republic's coniferous forests are facing the worst bark beetle infestation in known history. The amount of spruce wood damaged by bark beetles has risen steadily in the past few years, from 2 million cubic meters of spruce wood in 2015, more than 5.5 million cubic meters in 2017 to more than 13 million cubic meters in 2019. For this reason, the HOMED partners have concentrated their efforts in addressing the bark beetle problem, that could be used later as a model for other pests and pathogens.

Mapping forest disturbance (i.e. abiotic and biotic disturbance) is an essential tool for land management and research insights, especially in a global warming future (Anderegg *et al.* 2020). Recently, biotic disturbances (e.g. fungal diseases, insect outbreaks) have attracted more attention from researchers and politics. In fact, insect outbreaks are expected to grow up due to climate change, increasing in severity and frequency (Biedermann *et al.* 2019). During the last two decades, remote sensing has been increasingly used worldwide for detecting insect damage in forest ecosystems (Figure 1). However, many European studies were concentrated in few areas, lacking wide-scale approach (Senf *et al.* 2017). Multispectral data from satellite platforms were used to detect dead trees in single-date images or in time series (Meddens *et al.* 2013; Latifi *et al.* 2014; Bright *et al.* 2020). Since the free access of medium-resolution satellite images from Landsat and Sentinel missions, dense time series are now easily available. A careful selection of the acquiring time of the photo is a crucial issue and it depends on each biological system. For instance, bark beetle infestation has some phases, as well as a time-lag between the biotic phenomenon and the spectral response has been founded (Kautz 2014). While mature phases (red-attack and grey-attack) can be easily detected by remote sensing, differences in the spectral signature of the earliest phase (green-attack) have only been observed very recently (Abdullah *et al.* 2019). Besides remote sensing data, ground truth data (e.g. field survey, high-resolution aerial images…) are still necessary for calibration and validation of detection algorithms. Finally, separating biotic factors and others in forest loss might be more informative(Senf *et al.* 2017). Since previous studies (Seidl & Rammer 2017) suggested an interaction between bark beetle outbreaks and abiotic disturbances (such as wind, drought, and wildfire), disentangling different perturbation agents might help to better understand bark beetle outbreaks and to provide a new tool for forestry management.

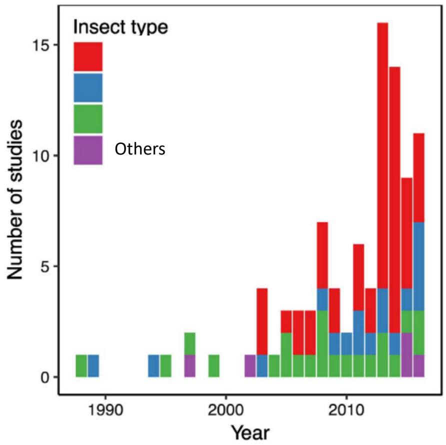

Fig. 1. Modified from Senf *et al.*, 2017)

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3. Results

1. Result 1: Macroscale survey in France

<u>Methods</u>

Two large geographic areas with bark beetle outbreaks were identified in NE France (Figure 2).

Fig. 2. Identification of the two regions of France, right above Grand-Est, right below Bourgogne-Franche-Comté.

In each region the presence of spots of trees killed by bark beetles was detected in October 2018 by SERTIT (mapping service of France) with the analysis of multispectral (13 bands from visible to medium infrared) images obtained from the satellite constellation Sentinel-2, belonging to the European programme Copernicus (European Spatial Agency). The spots were nested within a forest type categorisation provided by BD Forêt® 2.0 (IGN France) and by the Office National des Forêts (French Forest Service). The forest maps include homogenous areas of forest of a size larger than 0.5 ha, and they allow to distinguish dense coniferous forests, such as spruce and fir, from mixed stands. In addition, ownership is also provided at the same scale.

Later a check of the infested stands (spots) was carried out at various dates by the French Forest Service and the results were shared on the map obtained from the satellite survey. Satellites images from the same area were downloaded in March 2019 and compared with those of March 2018. Three bands of the visible spectrum and one band of the near-infrared were used for the comparison, all having a resolution on the ground of 10 m. To cover the whole study area, 21 image-squares, 100x100 km each, were used. In addition, a plane flight was carried out in April 2019 at specific areas to double-check the validity of the satellite detection and for a more precise identification of the damage.

The analysis of satellite images was carried out at the pixel level developing an algorithm based on the comparison of the satellite signal with the ground observations. Once the model has been tested under several terrain conditions, it has been applied to the whole area using a Support Vector Machine, which allows removing the noise of non-forest areas and other disturbances. The comparison of satellite images using three indexes (NRI near-infrared, NDVI Normalized Difference Vegetation Index, NBR medium infrared) were carried out between the images of March 2019 and March 2018. The comparison allowed to detect pure from mixed stands and spots infested by bark beetles. The spots exploited by forest managers were also detected. A threshold of 0.1 ha area was used for the spot identification. For the aim of the classification, the global performance was assessed using the Kappa index and the Overall Accuracy index.

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Results

The comparison 2019-2018 allowed us to identify 4 major types of spots:

- exploited spots, where attacked trees were removed by forest managers after the image of 2018;

- old spots, where dead trees were left on site and were present in the 2018 map;

- extended spots, where the area has increased between 2019 and 2018;

- new spots, where infested trees appeared in 2019.

More than 6,000 spots were detected for a total area of 1,659 ha (Fig. 3).

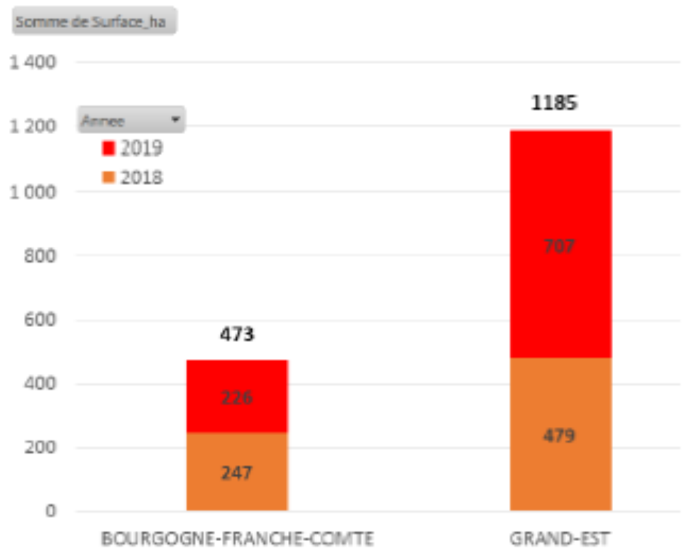

Fig. 3. Number of spots (>0.1 ha) of bark beetle damage in two regions of France in 2018 and 2019.

The spots were homogeneously distributed among districts within the regions and among owner types. The comparison between 2019 and 2018 allowed us to classify the spots in the four categories and the results are presented in Fig. 4.

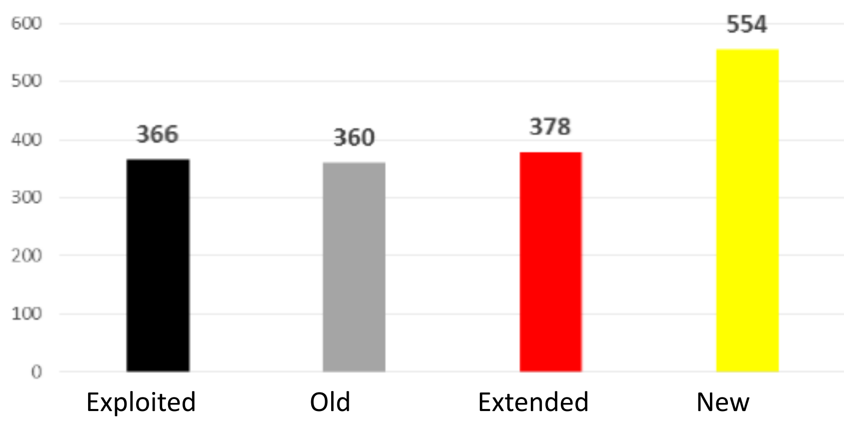

Fig. 4. Total area (ha) of spots of different origin present in March 2019.

A binary classification (positive/negative) of spot based on the satellite detection was compared with the ground detection of the tree condition (infested/healthy) derived from both aerial survey and ground check. The results are shown in Tables 1, 2, 3.

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Table 1. Satellite detection of spots (any size, raw data) vs tree condition on the ground.

	Satellite			
Tree condition	Infested	Healthy	% correct	% false negative
Infested	857	42	95	5
Healthy	1665	6406		
% correct	34		Kappa	0.42
% false positive	66		Precision %	81

Table 2. Satellite detection of spots (any size, data filtered with indexes) vs tree condition on the ground.

	Satellite			
Tree condition	Infested	Healthy	% correct	% false negative
Infested	782	117	87	13
Healthy	867	7204		
% correct	48		Kappa	0.56
% false positive	52		Precision %	89

Table 3. Satellite detection of spots (data filtered with indexes, area > 0.1 ha) vs tree condition on the ground.

	Satellite			
Tree condition	Infested	Healthy	% correct	% false negative
Infested	647	252	72	28
Healthy	205	7866		
% correct	76		Kappa	0.71
% false positive	24		Precision %	95

The use of raw satellite data involves a large overestimation of the number of spots, which is reduced to some extent by using the infrared vegetation indexes. A stronger reduction in the number of false positives was obtained when the area threshold of 0.1 ha was introduced. The reduction of the percentage of false-positive (24%) cases was associated with an increase in the percentage of false-negative cases (28%). The balance between the two was led by the spot size and the limitation is likely associated with the resolution of the satellite image (10 m). This resolution may allow an acceptable estimation of the beetle damage at a large scale whereas it is not fully reliable for precise identification of the spots at a smaller scale, especially when the spots are small. As detection of small spots is important for the deployment of the 'early detection-rapid intervention' approach, it would be desirable to detect spots at their very beginning, i.e. when only a few trees are infested. This approach does not seem feasible with Sentinel-2 images at a large scale and a higher resolution is required.

The data, however, are potentially very interesting for tracking the spatial population dynamics of the beetle and the large-scale approach may open the way to ecological studies so far not addressed.

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Macroscale study in the Czech Republic

Methods

The study is an area of High and Low Jeseniky Mountains – locality with the massive outbreak of bark beetle located in the North Moravian region (See Fig. 8) The total area of locality is 805,401 ha. Forests cover 335,365 hectares which represent 42% of the total area.

Fig. 8. Study area located in the North Moravian region

Since 2016 field data of infested trees cutting is collected all over the Czech Republic together with data collected by bark beetle traps. Since 2019 also remotely sensed data (satellite) is used for the localization of bark beetle spots. The bark beetle map is managed and provided by the Czech Forest Management Institute (CFMI). The image analysis itself is performed on the basis of a mosaic of satellite images from the PlanetScope system with a spatial resolution of 4.7 m/pixel, created of the current date for the entire territory of the Czech Republic. Detection of dry and freshly harvested spruce stands and subsequently all conifers use object-based image analysis based on the values of vegetation indices. Outputs are the result of semi-automatic classification. Two hundred bark beetle spots (training groups) were identified on the basis of the bark beetle map provided by CFMI and used to test the system. The minimum area of a single selected training group was 1 hectare (Fig. 9). Training groups were spatially joined with the set of cloud-free Sentinel images captured in May of every single year in the period 2016 – 2020, thus 5 Sentinel images were used. Calibration and atmospheric correction of sentinel images were performed using the SNAP (ESA) software and NDVI layers were created using ArcGIS software (ESRI).

The average value of NDVI of every single training group was calculated for every single year and compared. The range of NDVI decrease during the year, when the bark beetle cluster has appeared varies between 33 and 72%. That is why a decrease of NDVI of 30% in the spruce forest stands was selected as a limited value in the process of identification of bark beetle spots.

Outputs of identification of all bark beetle clusters in the period of 2016 – 2020 were vectorized into polygon features. Morphological aspects derived from a digital elevation model were spatially joined with resultant polygons and zonal statistic function was used to calculate average elevation and aspect for every single polygon.

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Results

A total of 343,530 bark beetle spots were identified in the period 2016 – 2020. Spots covered 23,472 ha in total. Spots and covered areas are described for every specific year in Table 3. The spread of bark beetle in time follows the west direction. In the years 2016 and 2017 the main outbreak was located on the east side of the studied locality in the area of Low Jeseniky Mountains. In the years 2018 and 2019 after the degradation of forest stands on the east side, the outbreak followed the west direction and attacked higher positions in High Jeseniky Mountains and the surrounding area. The spatial distribution of bark beetle spots is described in Figure 10 and 11.

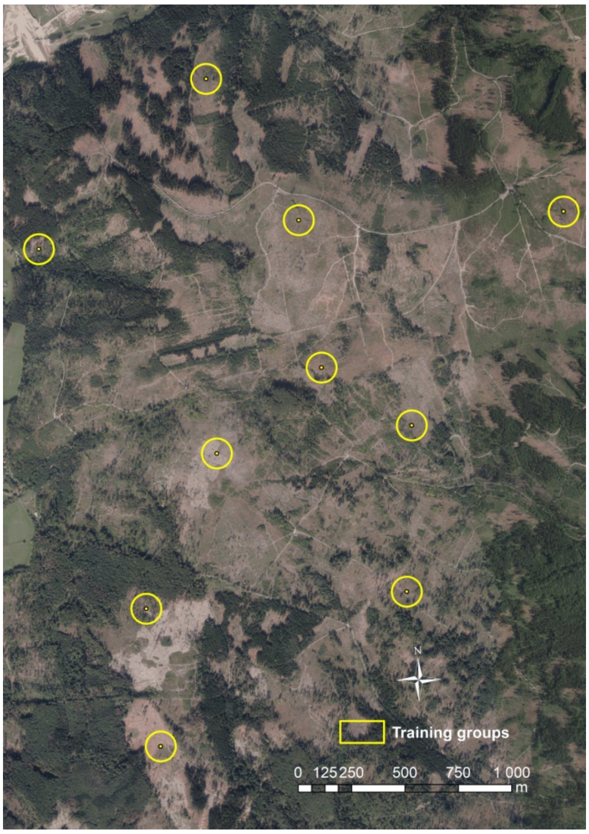

Fig 9. Sample of training groups

Table 1. Number of spots and covered area in specific periods.

Period	Spots	Area
2016 – 2017	60,185	3,990 ha
2017 – 2018	51,229	5,716 ha
2018 – 2019	112,524	7,356 ha
2019 – 2020	119,592	6,410 ha

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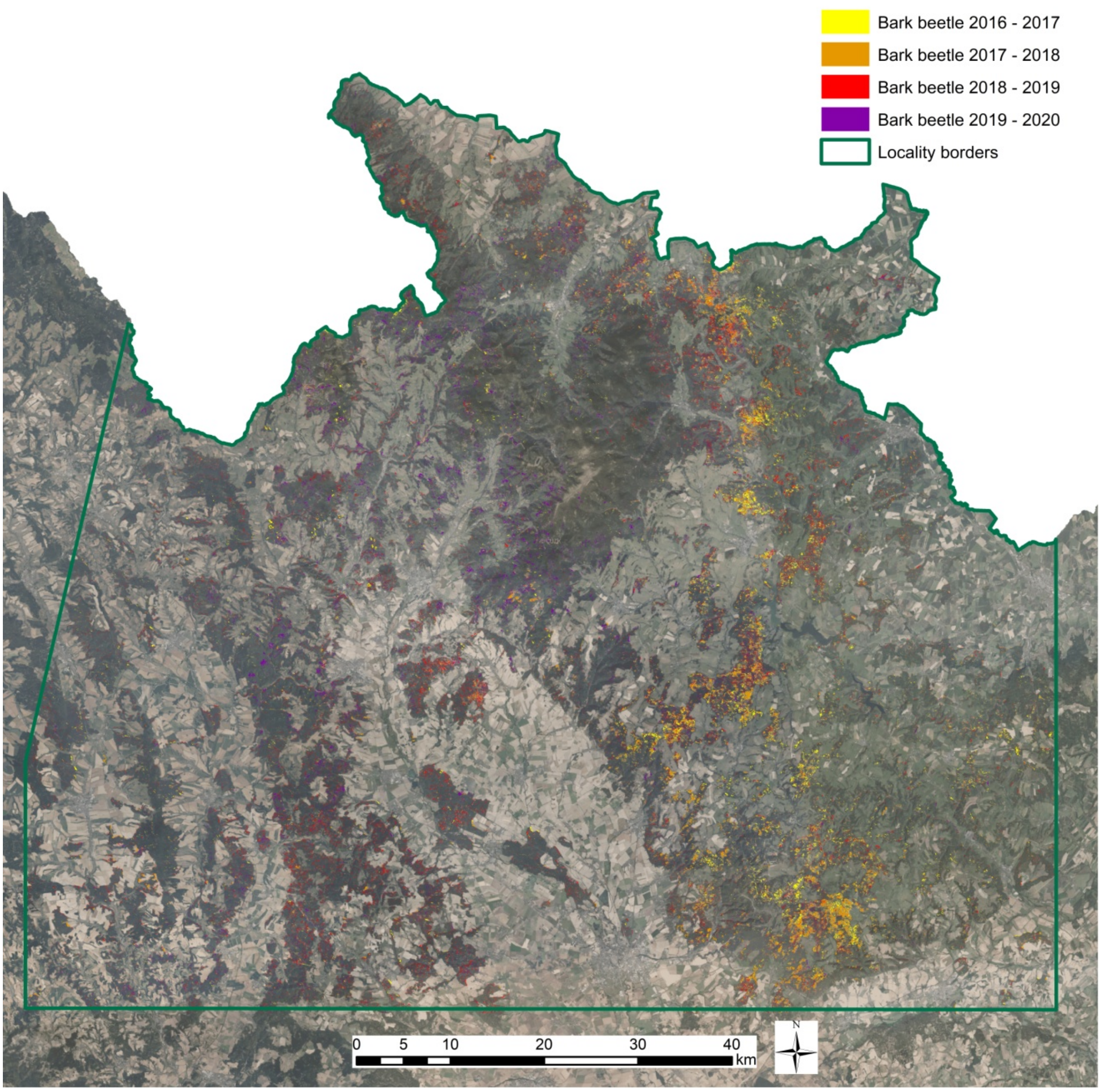

Fig. 10. Spatial distribution of bark beetle clusters between in the period of 2016 - 2020

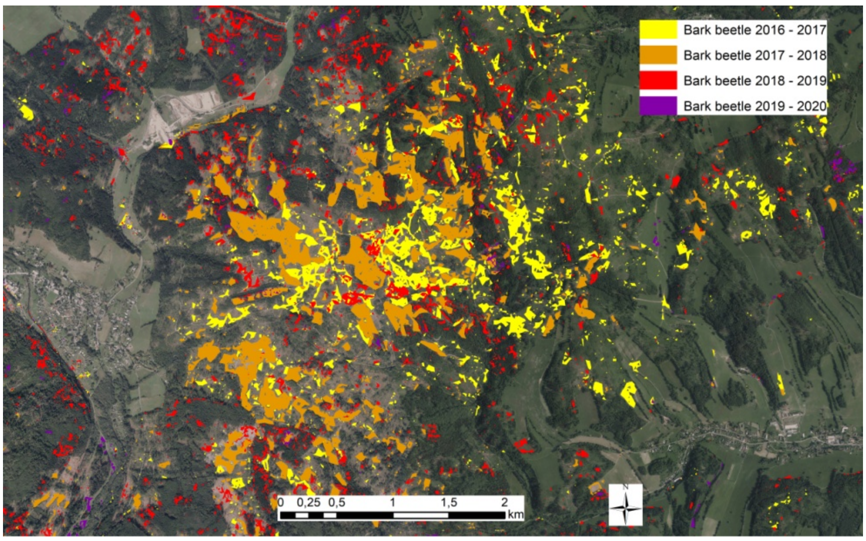

Fig. 11. Detail of massive bark beetle outbreak – central part of the Low Jeseniky mountains

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Elevation of bark beetle spots varies in the range between 213 and 1432 m with a mean between 400 and 700 m, where the largest spruce forest stands were located. The temporal trend shows an outbreak to reach higher altitudes because the High Jeseniky mountain range is in this direction.

The dominant orientation of slopes occupied by bark beetle follows the south-east and east direction with a very similar trend in every studied year. The decrease of south-oriented spots can be explained by the temporal process of the bark beetle outbreak. It starts in massive scale in 2014, but the study is dated in the period between 2016 – 2020 due to the missing Sentinel satellite data before 2015. At the beginning of outbreak, most probably south-oriented forest stands were damaged and that is why outbreak follows southeast and east-oriented slopes the most.

2. Result 2: Mesoscale survey in Italy

<u>Methods</u>

The area of interest is the Gares valley in Belluno province, NE-Italy, for about 25 km^2. This locality has been hit by a European bark beetle (Ips typographus) infestation from 2017. During Vaia windstorm in October 2018 many hectares of trees were felled. Recently, the infestation has resumed, starting from previous spots and wind-damaged areas (Figure 5). The Gares valley was a good candidate for this study due to its forest disturbance history, for availability of climatic data and high spruce percentage in forest composition. To avoid intense shade disturbance, we focused only on south-facing slope.

Satellite images taken by Sentinel 2 constellation were used. Sentinel 2 data consists in 13-band multi-spectral images ranging from visible light to SWIR (short-wave infrared light). Four bands (2, 3, 4 and 8) have 10-meter resolution, six bands (5, 6, 7, 8a, 11 and 12) have 20-meter resolution and three bands (1, 9, 10) have 60-meter resolution. Satellite images used for this study were downloaded from Copernicus repository (https://scihub.copernicus.eu) as 1-C level products. By using sen2Cor algorithm (version 280) in SNAP software (http://step.esa.int/main/), images were processed to 2-A product. We checked for free-cloud images in our study area and we selected one image for each year. We focused on the end of August, since the previous study showed good NDVI performance in this period (Abdullah *et al.* 2019).

To assess changes in forest health, we used a comparative approach across time-series images. First, we calculated the NDVI index for each year. Then, a difference raster was computed for each couple of years. To avoid non-forested pixels we created a mask for spruce coverage. We used satellite images taken on 22nd of October 2015, as an initial condition. As we assumed that at such time broadleaves trees and meadows had low NDVI values, we selected only pixel with high NDVI value (range 0.75-0.95).

Finally, we calculated the difference in pixel values between following years. We set threshold values (- 0.1) on NDVI-difference outputs in order to point out NDVI-falling spots. We used ArcGIS pro for raster calculation and processing and QGIS for result visualization and map printing.

Apparently, the cause of forest cover losing is not distinguishable by remote sensing approach. To address this issue, we carried out a field survey. We determined the disturbance cause for each NDVI-falling spot in order to disentangle bark beetle damage from windthrow gaps. Then, disturbance areas were poligonized and assigned to a disturbance category (bark beetle or wind) by field data.

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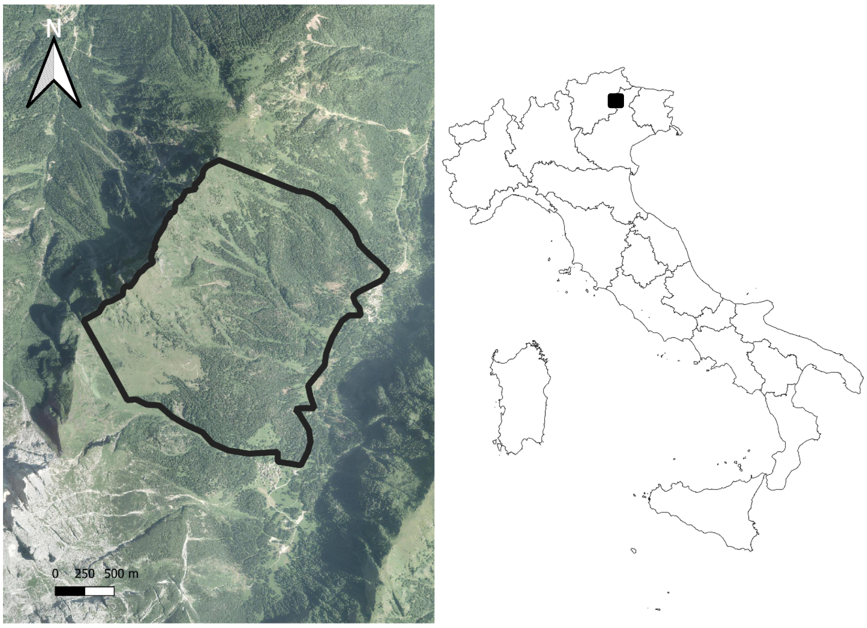

Fig. 5: Area of interest in NE Italy

<u>Results</u>

Once damaged polygons were validated, we estimated the total damaged area using GIS software (Figure 6 and 7). Also, a recent climatic history of the valley was retrieved from local meteorological stations (data are available to download from ARPAV website, https://www.arpa.veneto.it). We found the beginning of bark beetle outbreak in 2017 and estimated almost 3 hectares of damaged forest in our study area. Probably, the previous dried years (mean rainfall: 1,224 mm/year from 2015 to 2017) might be the cause. The outbreak has proceeded in 2018, damaging other 2 ha of forest related to previous-year spots (median of distance between 2018-spots and 2017-spots: 25 meters). At the end of 2018, Vaia windstorm severely hit the area and it led the loss of 25.8 ha. Meanwhile, the outbreak decreased during 2019. In this study area, the fallen trees have not been removed from the stands. During this year, we found a weak resumption of bark beetle attack in terms of spatial extension (1.3 ha of damaged forest). Nevertheless, we found some small spots (3-4 trees) of new infestation and infested trees with weak change in needle colour. These situations are not detectable by satellite images because of small dimension or weak changing in spectral response.

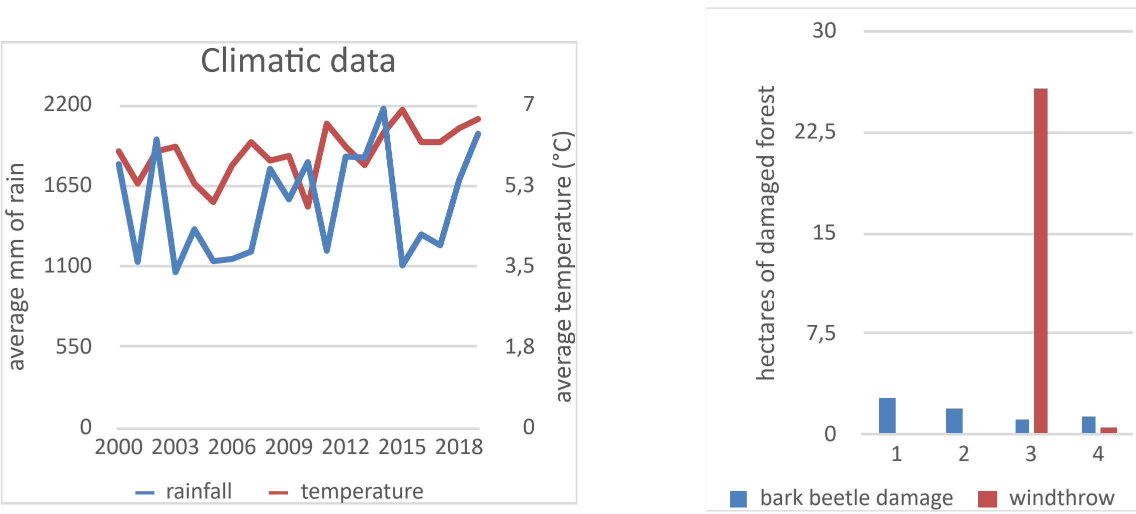

Fig. 6: Climatic data retrieved from ARPAV monitoring network and estimated amount of damage by source (e.g. bark beetle and wind disturb)

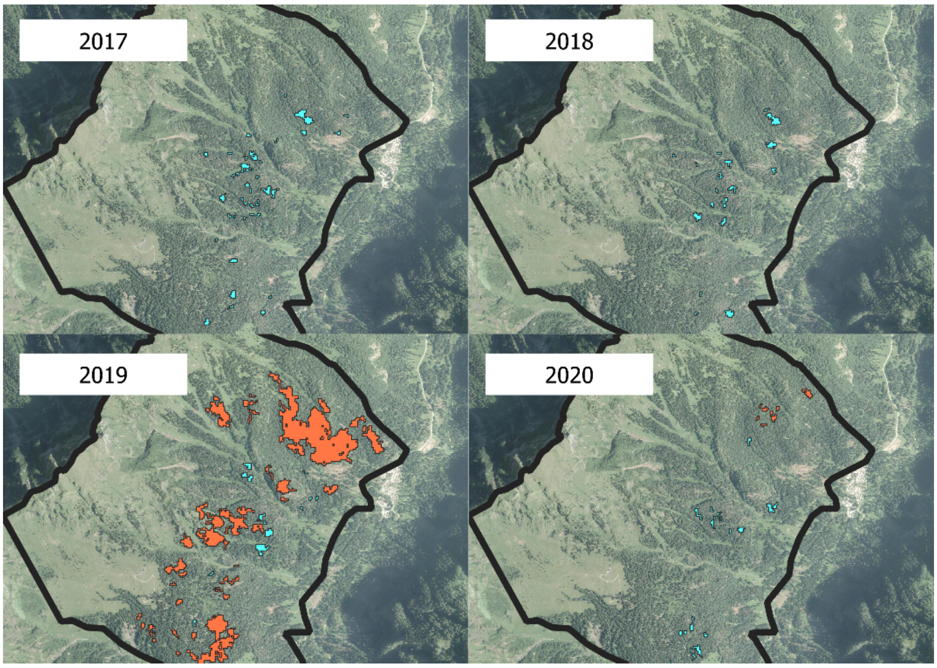

Fig. 7: Time series images depicting annual change in forest cover (light blue: insect outbreak; orange: windthrow gaps)

This first study pointed out limitations and potential development of research. We worked only in south-facing slopes in order to avoid shadows and poorly lighted slopes. In following surveys, topographic correction should be considered as pre-processing step. We found no difference in values of vegetation indices between windthrows on the ground and standing bark-beetle-killed trees. Nowadays, our remote sensing approach is not able to disentangle between wind and bark beetle damage. Field surveys or high-resolution aerial photography are still important tools for remote sensing calibration and assessment at this mesoscale. Finally, spatially explicit databases are opening new perspectives in understanding dynamics and interaction with climatic and abiotic variables, even more important under a climate change perspective.

3. Result 3: Microscale survey in Czech Republic

Methods

With the aim of identifying bark beetle-infested trees that were still green, in 2019 surveillance using Unmanned Aerial Vehicle (UAV) has been carried out in two selected forest stands in the South-Moravian region in the Czech Republic in an area of 420 ha. The survey was carried out using UAV with a multispectral camera.

The study was carried out in two forest stands located in the Forest training district Krtiny, South-Moravian Region, Czech Republic. Site 1 „Pokojná“ covers an area of 230 ha, site 2 „Jedovnice“ covers an area of 190 ha (Fig. 12). Both studied sites were monoculture spruce forest stands with simile age – 80 years.

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Fig. 12. Localization of studied sites Pokojná and Jedovnice

Both studied sites were covered by multispectral data captured by UAV eBee SenseFly equipped by multispectral camera Parrot Sequoia+ (See Fig. 13). The predefined flights were set at a flight level of 60 m with an overlap of images of 80 % to produce multispectral layers with the spatial resolution of 3 cm and digital surface models with a spatial resolution of 5 cm.

Fig. 13. eBee SenseFly (left), Parrot sequoia+ (right)

Aerial data were processed using Agisoft Photoscan software to produce a multispectral layer consisting of 4 bands: Green, Red, Red Edge, and Near-infrared part of the electromagnetic spectrum.

To identify the position of every single tree data processing was carried out in the following steps: 3D point cloud was created using the photogrammetry of overlapping images captured in green, red and red edge bands. Resultant point clouds were interpolated into the digital surface models. The inverse watershed process was used to create a canopy height model and to identify all individual trees of studied forest sites (Fig. 14).

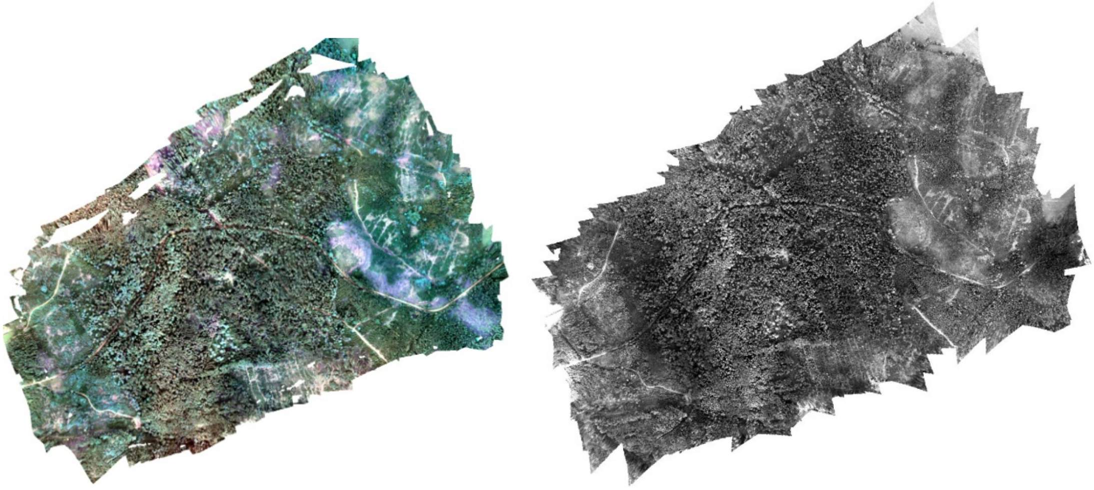

Fig. 14. Multispectral image (left) and digital surface model of locality Pokojná (right)

Multispectral data was processed using ArcGIS software to create the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge Index (NRDE) of both studied sites. A random forest classifier was used to determine healthy, damaged, and dead trees (see Fig. 15).

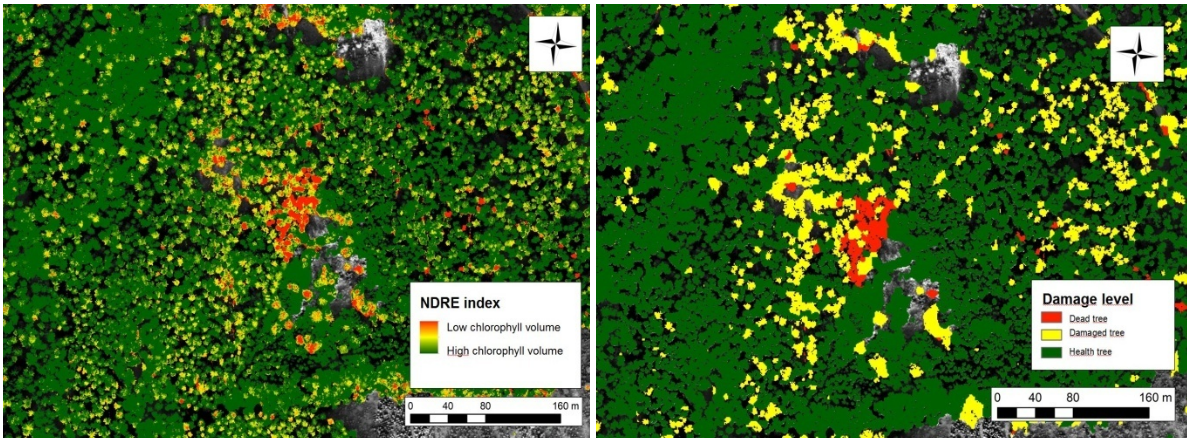

Fig. 15. NDRE index (left) and damage level of trees (right)

Field observation was carried out to identify and localize a number of dead and damaged (infested still green) trees. The position of trees was recorded using geodetic GPS Topcon HyperPro in combination with Trimble GeoXH. The accuracy of measuring was enhanced using the real-time kinematics (RTK) navigation technique. A total of 163 dead or damaged trees were recorded in the research site „Pokojná" and 127 of dead or damaged trees were recorded in the research site Jedovnice. Resultant data were subsequently spatially overlaid and evaluated with aerial outputs.

Results

Aerial data provide highly accurate outputs to identify infected and dead trees attacked by the bark beetle. Results describe the reliability of detection of the European spruce bark beetle attack using UAV in the range of 94% - 97% in case of dead trees and 78% - 85% in case of damaged (still green) trees (See Tab. 4,5).

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Tab. 4. Comparison of aerial outputs with the field verification in the research site Pokojná

Vegetation index	Damaged trees identified in the field	Number of trees in compliance with aerial outputs	Accuracy of UAV detection	Dead trees identified in the field	Number of trees in compliance with aerial outputs	Accuracy of UAV detection
NDVI	37	29	**78 %**	126	118	**94 %**
NDRE	37	31	**84 %**	126	120	**95 %**

Tab. 5. Comparison of aerial outputs with the field verification in the research site Jedovnice

Vegetation index	Damaged trees identified in the field	Number of trees in compliance with aerial outputs	Accuracy of UAV detection	Dead trees identified in the field	Number of trees in compliance with aerial outputs	Accuracy of UAV detection
NDVI	28	22	**79 %**	99	93	**94 %**
NDRE	28	23	**82 %**	99	96	**97 %**

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