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Detecting Bark Beetle-Induced Changes in Coniferous Alpine Forests Using Sentinel-2 Time Series and In-Situ Felling Data

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Abstract:
Mapping forest areas affected by bark beetle infestation using remote sensing imagery is crucial for effective hazard management and risk assessment. This study evaluates the potential of Sentinel-2 satellite image time series (SITS) in combination with in-situ felling data to detect bark beetle infestation in coniferous forests in Pokljuka, Slovenia. The analysis uses the CuSum method, all Sentinel-2 spectral bands and key spectral indices such as NDVI and NBSI to identify changes and areas of forest loss in the period 2017–2021. The resulting geospatial dataset, which integrates these remote sensing results with field data, serves as a basis for further analyses using advanced machine and deep learning methods and various remote sensing data such as hyperspectral datasets. In addition, we found that the most useful bands for detecting the loss of alpine coniferous forests are SWIR (B11, B12), Red (B04) and Red-Edge (B05) as well as the two spectral indices used, NDVI and NBSI.

1. Introduction

In recent years, outbreaks of bark beetles (Ips spp.), exacerbated by windthrow, sleet and prolonged drought, have contributed significantly to the decline of conifer-dominated forests in Central Europe (Bárta et al. 2021). Spruce forests (Picea abies) are particularly at risk, where an unsuitable species composition and extreme weather events have created favourable conditions for infestation. In Slovenia, the damage caused by bark beetles in spruce forests has steadily increased since 2014, with 689 hectares affected in 2020 alone. Although bark beetles typically attack weakened or stressed trees, high population density can lead to mass infestation of otherwise healthy individuals, resulting in widespread mortality and posing significant challenges to forest management (Potterf et al. 2019).

Traditional field monitoring methods for detecting bark beetles are labour-intensive and often unsuitable for large-scale outbreaks. Remote sensing, in particular the use of Sentinel-2 satellite imagery, has proven to be a powerful tool for detecting infestations at different stages. Early detection, especially in the green infestation phase, remains a challenge but is crucial for timely intervention. Most studies focused on the post-emergence stages (Kautz et al. 2024) and achieved an accuracy of 70–90% using optical remote sensing data from MODIS, Landsat and Sentinel-2. Sentinel-2 has shown better early detection performance (67%) than Landsat-8 (36%) due to its higher spatial, spectral and temporal resolution. Studies have shown that infestation in the early stages (green infestation) shows spectral differences, especially in the red edge region and in the short-wave infrared range (Dalponte et al. 2022). Hyperspectral data from the air and unmanned aerial systems have been tested for early detection at the local level, but are not suitable for monitoring at the national level. Most studies rely on spectral indices (e.g. NDVI, NDWI, DWSI) and apply classification methods such as Random Forest (RF) and Support Vector Machines (SVM) to distinguish between healthy and infested trees at different stages of bark beetle development (Bárta et al. 2021; Kautz et al. 2024). Convolutional neural networks (CNNs) have also shown promise in detecting infested trees in high-resolution multispectral data, although they struggle with limited training data and high computational costs. Most reference datasets are derived from aerial or satellite imagery and are usually represented as point-based observations with limited spatial accuracy, making integration with remote sensing analyses at the pixel level difficult.

Alternative change detection methods include dense SITS approaches, which are more robust than traditional bi-temporal analyses as they capture phenological and seasonal variations, long-term changes and abrupt shifts. Techniques such as Continuous Change Detection and Classification (CCDC), LandTrendr and Breaks for Additive Season and Trend (BFAST) are widely used, with BFAST's CuSum algorithm being widely used in radar-based studies of forest change (Ygorra et al. 2024). However, these methods are not yet specifically tailored to the detection of bark beetles.

In response to the increasing frequency and intensity of bark beetle outbreaks — caused by climate change and past management practises such as large-scale planting of spruce trees outside their natural range — there is a growing need for coordinated monitoring systems at national, European and global levels. These systems need to provide spatially explicit and temporally consistent data sets that support evidence-based responses to forest disturbances. Satellite imagery, especially from freely available missions such as Sentinel-2, provides a harmonised and objective global observation platform that enables consistent data collection across regions and facilitates the timely detection of environmental stressors such as bark beetle outbreaks (Hlásny et al. 2019).

In this research, we aim to answer the following questions:
1) How can Sentinel-2 time series and in situ felling data be integrated with time series change detection techniques, such as the CuSum algorithm, to create scalable and robust datasets for further analysis with advanced deep learning methods and to obtain more spectrally precise datasets, such as those from hyperspectral sensors?

2) Which spectral bands and indices of Sentinel-2 are most useful for bark beetle areas and what do their time series look like?

2. Material and methods

2.1 Study Area

Pokljuka is a forested plateau in the Triglav National Park in north-west Slovenia. It is predominantly covered with spruce (Picea abies), with smaller areas of silver fir (Abies alba), European beech (Fagus sylvatica) and sycamore (Acer pseudoplatanus). Historically, the forests were heavily exploited in the 18th century and subsequently converted into conifer-dominated stands, which favoured spruce monocultures in particular. The study area covers an area of about 750 km² and is divided into about 1470 forestry compartments. The altitude ranges from 410 m to 1930 m, with an average of 1030 m. The region has an average annual temperature of 7.6 °C and an average rainfall of 1600 mm. The forest types are categorised as subalpine and montane spruce forests.

These forests play an important ecological, protective and socio-economic role, but are increasingly vulnerable to natural disturbances, especially wind and snowthrow. In recent years, the Pokljuka region has seen a notable increase in salvage logging due to bark beetle outbreaks, following the trends observed nationwide (Figure 1). The prevalence of homogeneous spruce stands has contributed to the extent of the infestation. As a result, the landscape has changed significantly both ecologically and visually. Numerous formerly forested areas have been replaced by clearings and regrowing stands.

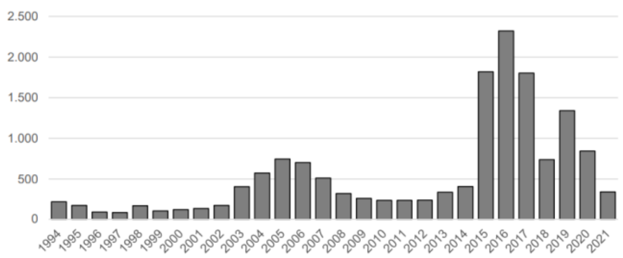

Figure 1: The graph shows the volume of logging due to bark beetle infestation (sanitary logging) from 1994 to 2019 in Slovenia, measured in thousands of cubic metres. Our results are part of the period 2017–2021 (ZGS 2022).

2.2 Datasets and Sources Used for Change Detection

Dataset	Source	Purpose
Sentinel-2	Copernicus / ESA	Time series generation and spectral index calculation.
database TIMBER	Slovenian Forest Service (SFS)	Reference for sanitary deforestation due to bark beetle.
Google Earth Historical Imagery	Google Earth	Visual validation of detected spectral changes.

Table 1. Overview of the input datasets used in the study.

The analysis was based on three main data sources: Sentinel-2 multispectral imagery, in-situ sanitary logging records from the TIMBER database, and historical aerial imagery available in Google Earth. Sentinel-2 data were used to construct time series and derive vegetation indices, while TIMBER records served as a reference for bark beetle-related disturbances. Google Earth imagery supported visual validation of detected spectral changes. An overview of the input datasets is provided in Table 1.

2.3 Sentinel-2 Time Series and Vegetation Indices

The Sentinel-2 satellite images provide high-resolution, multispectral observations that are well suited for vegetation monitoring. In this study, all available Sentinel-2 spectral bands (B01–B12), except B10, were used together with cloud probability and classification layers (CLP and CLM) to create dense satellite image time series (SITS) that allow the derivation of important biophysical parameters relevant for forest health assessment.

In this study, the Sentinel-2 SITS were pre-processed using the Sentinel Hub Service and the eo-learn Python library, applying cloud masks (CLM and CLP) to ensure data quality in the pre-processed SITS.

Although all bands were initially considered, only the most relevant spectral bands and indices were used for further analysis due to their sensitivity to bark beetle-induced changes and findings from previous studies (Dalponte et al. 2022; Kautz et al. 2024). Less informative bands for terrestrial applications (e.g. B01 and B09) were excluded in later steps due to their limited contribution to vegetation-related signals.

Vegetation indices were calculated to capture certain aspects of forest condition. In particular, the Normalised Difference Vegetation Index (NDVI) (1) and the Normalised Bare Soil Index (NBSI) (2) were used to monitor green cover and soil stress, respectively. These indices are sensitive to stress-induced changes in the canopy of coniferous forests and make it possible to track both gradual and abrupt changes in vegetation.

$$NDVI = \frac{B08-B04}{B08+B04}, \quad (1)$$

$$NBSI = \frac{(B11+B04)-(B08+B02)}{(B11+B04)+(B08+B02)}, \quad (2)$$

2.4 CuSum (Cumulative Sum) Algorithm

The Cumulative Sum (CuSum) algorithm, originally developed for statistical quality control (Lucas, 1982), is a method for detecting changes when analysing temporal signals. It has been used in many fields such as finance and industrial monitoring to detect anomalies in large data streams (Manogaran and Lopez, 2018). However, its application in environmental monitoring and optical SITS is still relatively limited. Recent studies have shown its potential for forest disturbance detection, especially using radar time series such as Sentinel-1 (Manogaran and Lopez, 2018).

CuSum was selected for its simplicity, low computational cost and proven effectiveness in highlighting subtle but systematic deviations in vegetation dynamics that characterise early-stage bark beetle infestations. To avoid false detections in non-forested areas, the analysis was restricted to forested pixels as defined in the national land use map. The forested areas were delineated using the official RABA (Record of Agricultural and Forest Land

Use) layer of the Ministry of Agriculture, Forestry and Food (MKGP).

In this study, the CuSum algorithm was adapted for use with vegetation index time series derived from Sentinel-2 imagery to detect changes caused by bark beetles. The algorithm identifies deviations by calculating the cumulative sum of residuals from the mean (3).

$$R_{sum\ j} = \sum_{i=1}^{n_{images}} R_{ij},\ R_{ij} = VI_{ij}^{0} - \overline{VI_j^0}, \tag{3}$$

where VI_{ij}^{0} = vegetation index of pixel j in image i

$\overline{VI_j^0}$ = average vegetation index value for that pixel over the entire SITS.

The algorithm recognises the time of change by identifying the point at which the cumulative sum reaches its maximum (or minimum). This point corresponds to a potential disturbance event in the vegetation dynamics. Figure 2 shows an example of the CuSum signal and its breakpoint for a single pixel affected by bark beetle infestation.

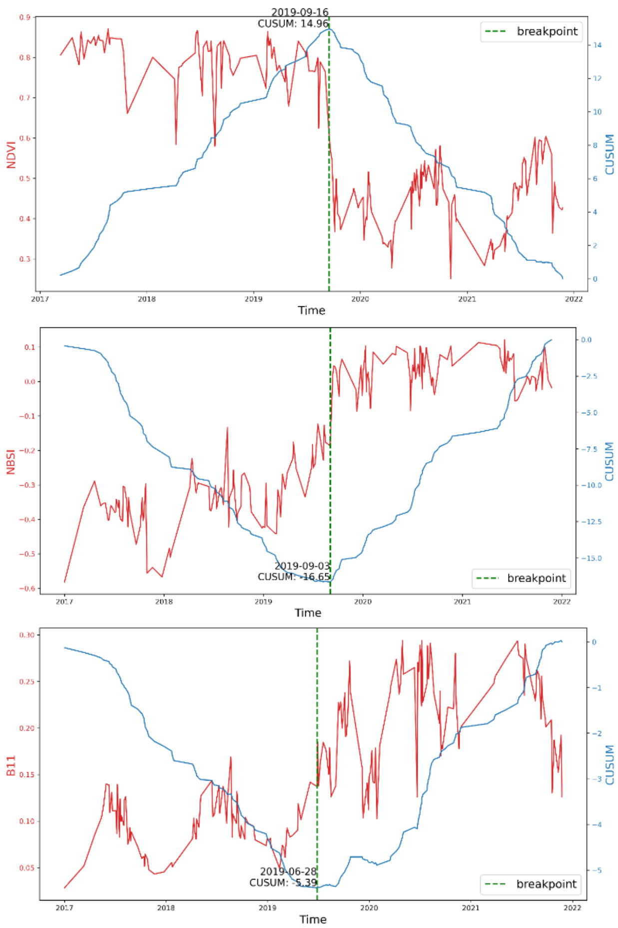

Figure 2. Example of CUSUM-based change detection using NDVI (top), NBSI (centre), and SWIR band B11 time series (bottom) at a coniferous forest site in Pokljuka. The vertical line indicates the point of detected change corresponding to the probable time of disturbance.

2.5 Reference in-situ data from database TIMBER

For validation purposes, a spatially and temporally explicit reference dataset from the tree felling database (TIMBER), which is managed by the Slovenian Forest Service (SFS), was used. The TIMBER database contains records of tree felling, including the cause of the intervention (e.g. felling caused by insects), the date of felling, the number of specific tree species and the harvested volume, covering all managed forest areas in Slovenia.

Logging caused by bark beetles was identified by the attribute cause of intervention, using the category insect damage as a proxy for bark beetle infestation. According to internal analyses, about 99% of the entries in this category are related to bark beetle outbreaks, which makes it a reliable indicator for this type of disturbance. Only these events were selected for the creation of the reference infestation masks.

2.6 Accuracy Assessment

Due to the different spatial resolution and semantic representation, a direct comparison at pixel level or temporal level between the in-situ reference data from the TIMBER database and the results of the change detection is not possible. The TIMBER data is available at the forest compartment level, while the satellite-based change detection is performed at the pixel level. Furthermore, the exact geographical location of the felled trees within each compartment is not explicitly recorded.

To circumvent this, we have introduced an indirect validation approach. Bark beetle-related deforestation events from the TIMBER database were aggregated at compartment level and temporally matched with Sentinel-2-based time series of vegetation indices (e.g. NDVI). By overlaying the spatial extent of sanitary deforestation with the corresponding pixel-level changes determined using the CuSum algorithm, we assessed the temporal and phenological correspondence between the observed changes and the reported deforestation activities.

Figure 3 illustrates this relationship by comparing the number of felled conifers recorded in the TIMBER database (blue bars) with the NDVI time series of a corresponding Sentinel-2 pixel (green line). The graph shows a general correspondence between the decrease in NDVI values and the time of increasing deforestation, indicating a correspondence between the changes recorded by the satellites and the ground-based in-situ data.

This approach makes it possible to interpret each detected change at the pixel level in the context of a corresponding record on the ground at the forest compartment level, allowing for approximate spatial and temporal validation despite different resolutions.

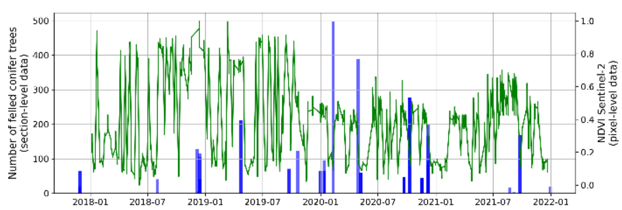

Figure 3. Temporal relationship between the number of felled conifers (blue bars, derived from the TIMBER database at forest compartment level) and Sentinel-2 NDVI values (green line, pixel-level data) at a bark beetle-infested site in the Pokljuka region. The NDVI time series shows a decrease in vegetation greenness coincides with the increase in remediation activities, indicating a correspondence between remotely sensed changes and ground-based observations.

2.7 Validation

A complete quantitative validation based on a newly created, independent reference dataset was not carried out. Due to resource and time constraints, no additional ground truth dataset was created in addition to the TIMBER-based forest compartment data already described.

Instead, the pixel-level change detection results were validated by a visual comparison with the available historical aerial imagery in the Google Earth historical image archive. This approach allowed an approximate spatial and temporal assessment of the plausibility of the detected changes in areas identified as affected by bark beetle outbreaks. Selected pixels labelled by the CuSum algorithm as locations of change were visually compared with high-resolution aerial images of the corresponding time period. In most cases, a general match was found when the satellite images showed visibly damaged or cleared crown areas in the same season or year as the detected change.

Although this method lacks quantitative rigour, it provided additional visual support to confirm the spatial plausibility of the observed forest changes. Future applications should — at least in part - collect data at a finer spatial resolution, ideally in the form of georeferenced point observations that explicitly indicate forest disturbance. Such data would significantly increase the reliability of the validation of bark beetle change detection, as it would allow a more accurate spatial and temporal comparison with the satellite-based results.

3. Result

3.1 Breakpoint Magnitude Maps and Time Detection

Using the CuSum algorithm, we generated breakpoint magnitude and time of change maps for two vegetation indices—NDVI and NBSI—to detect significant spectral changes in coniferous forest areas. The goal was to spatially and temporally localize potential forest disturbances between 2017 and 2021.

Figure 4 presents time of change maps, showing the estimated month and year when a spectral change occurred. The estimation is based on the point of maximum cumulative deviation from the mean within each pixel's time series. The results are displayed separately for NBSI and NDVI, illustrating differences in timing and sensitivity between the two indices.

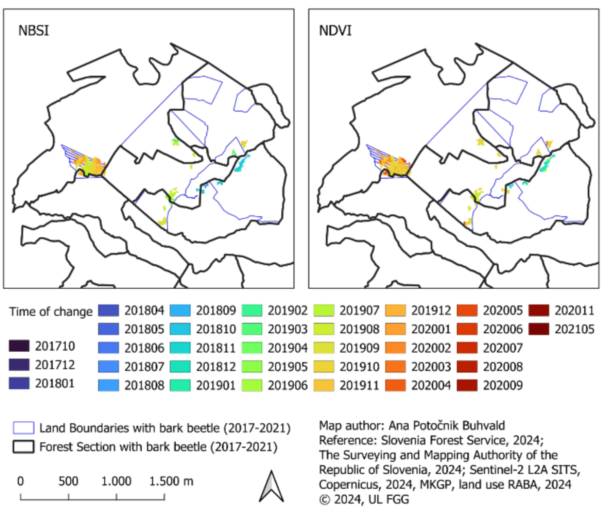

Figure 4. Time of detected spectral change based on CuSum analysis of NBSI (left) and NDVI (right) time series. Colours represent the estimated month and year of change between 2017 and 2021. Black outlines indicate forest sections with bark beetle-related logging recorded in the TIMBER database, and blue lines show cadastral land boundaries.

3.2 Bark Beetle Geospatial Dataset

The final bark beetle mask was generated by identifying pixels that exhibited high breakpoint magnitudes in both NDVI and NBSI time series, as determined by the CuSum algorithm. To increase specificity, only pixels within forest compartments marked in the TIMBER database as logged due to insect infestation were retained. The recorded cause of logging in these cases is classified as insect damage, with approximately 99% of cases attributed to bark beetle outbreaks.

Figure 5 shows the spatial intersection of spectral change maps with in-situ sanitary logging data, resulting in a high-confidence raster mask of bark beetle-affected areas for the period 2017–2021. This geospatial dataset is openly available and can be used for model training, forest monitoring applications, or validation of other disturbance detection methods (Potočnik Buhvald, 2025).

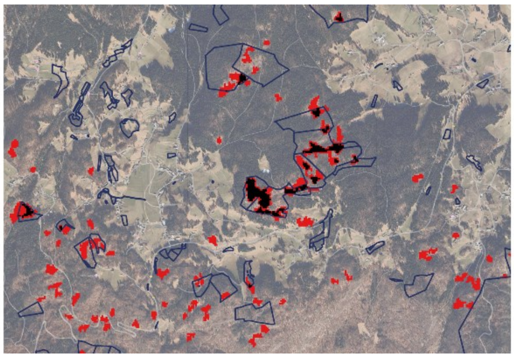

Figure 5. Final bark beetle disturbance mask (black), change detection mask from Sentinel-2 (red), and forest compartments with insect-related logging from the TIMBER database (blue) overlaid on aerial imagery.

3.3 Identification of the Most Robust Spectral Bands

We validated the dataset by analyzing Sentinel-2 time series for polygons separately detected in 2018, 2019, and 2020 (Figure 6). Each polygon represents an potential area affected by bark beetles and includes the year of detection. This dataset allows for precise temporal and spatial identification of bark beetle outbreaks, serving as an additional input parameter for further modelling efforts. The resulting geospatial dataset is highly versatile, enabling integration with various types of remotely sensed data to enhance analyses and provide explicit spatial and temporal context.

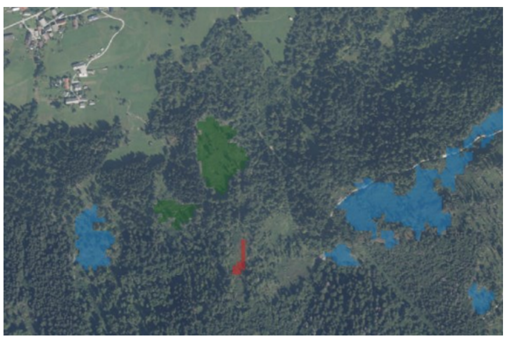

Figure 6. Prepared geospatial dataset of bark beetle detection in different years. Red area is affected in 2018, blue in 2019 and green in 2021.

This analysis focused on calculating yearly differences in spectral band values to identify the most significant spectral bands for detecting bark beetle infestations (Figure 6). Result shows that the most important are SWIR (B11 in B12), red (B04) and red-edge (B05) spectral bands.

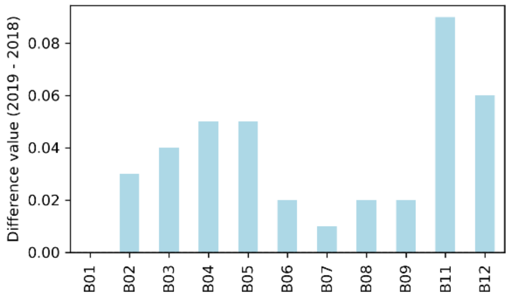

Figure 7. Yearly difference values (2019–2018) for all Sentinel-2 bands (B01–B12). The analysis highlights the most significant spectral bands for detecting bark beetle-induced changes, with SWIR bands (B11, B12), the red band (B04), and the red-edge band (B05) showing the largest differences. These features indicate key spectral responses to vegetation stress and disturbance during the infestation period.

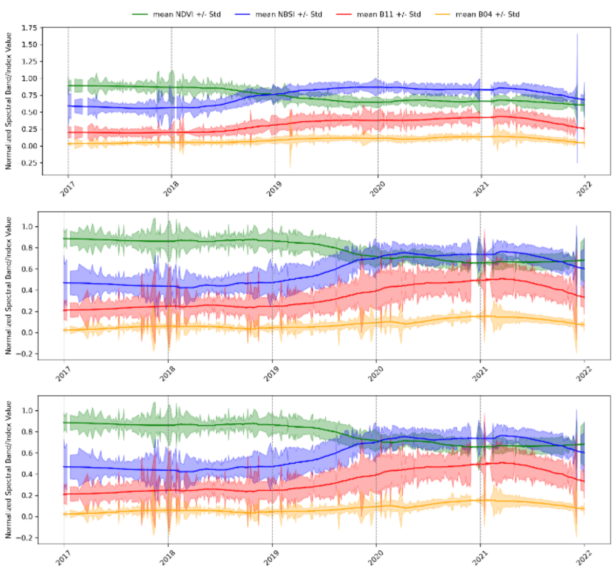

Figure 8. Time series of normalized spectral band/index values for NDVI (green), NBSI (blue), B11 (red), and B04 (orange) with mean values and standard deviation (± std) for 2018 (first), 2019 (second) and 2020 (third) which shows notable changes during the bark beetle infestation period for specific year and dataset.

For yearly detected areas, we computed mean SITS values with standard deviations (± std), visualized in the time series plot (Figure 8). The plot highlights the temporal trends in key spectral indices (NDVI, NBSI) and spectral bands (B04, B11), showing changes in vegetation health and soil exposure over time. This approach confirms the reliability of the dataset in capturing bark beetle-induced changes and provides a robust framework for further analysis and modelling.

4. Conclusion

This study demonstrates the potential of integrating time series of Sentinel-2 satellite image with in-situ sanitary wood records to detect bark beetle-induced changes in coniferous forests using the CuSum change detection algorithm. The approach, based on NDVI and NBSI spectral indices, successfully identified areas with significant spectral deviations and produced a time-resolved bark beetle disturbance map for the period 2017–2021. The resulting dataset, now available as an open-access product on Zenodo (https://doi.org/10.5281/zenodo.15260584), can support various applications, including forest monitoring, early warning systems and deep learning model training.

Although no quantitative accuracy assessment was performed due to the limited spatial resolution of the available in situ data, visual comparison with aerial images and TIMBER deforestation records confirmed the spatial and temporal plausibility of the detected changes. Future applications should — at least partially— - collect data with a finer spatial resolution, ideally in the form of geo-referenced point observations that explicitly indicate forest disturbances. This would allow a more precise and statistically robust validation of remote sensing-based change detection methods.

Acknowledgements

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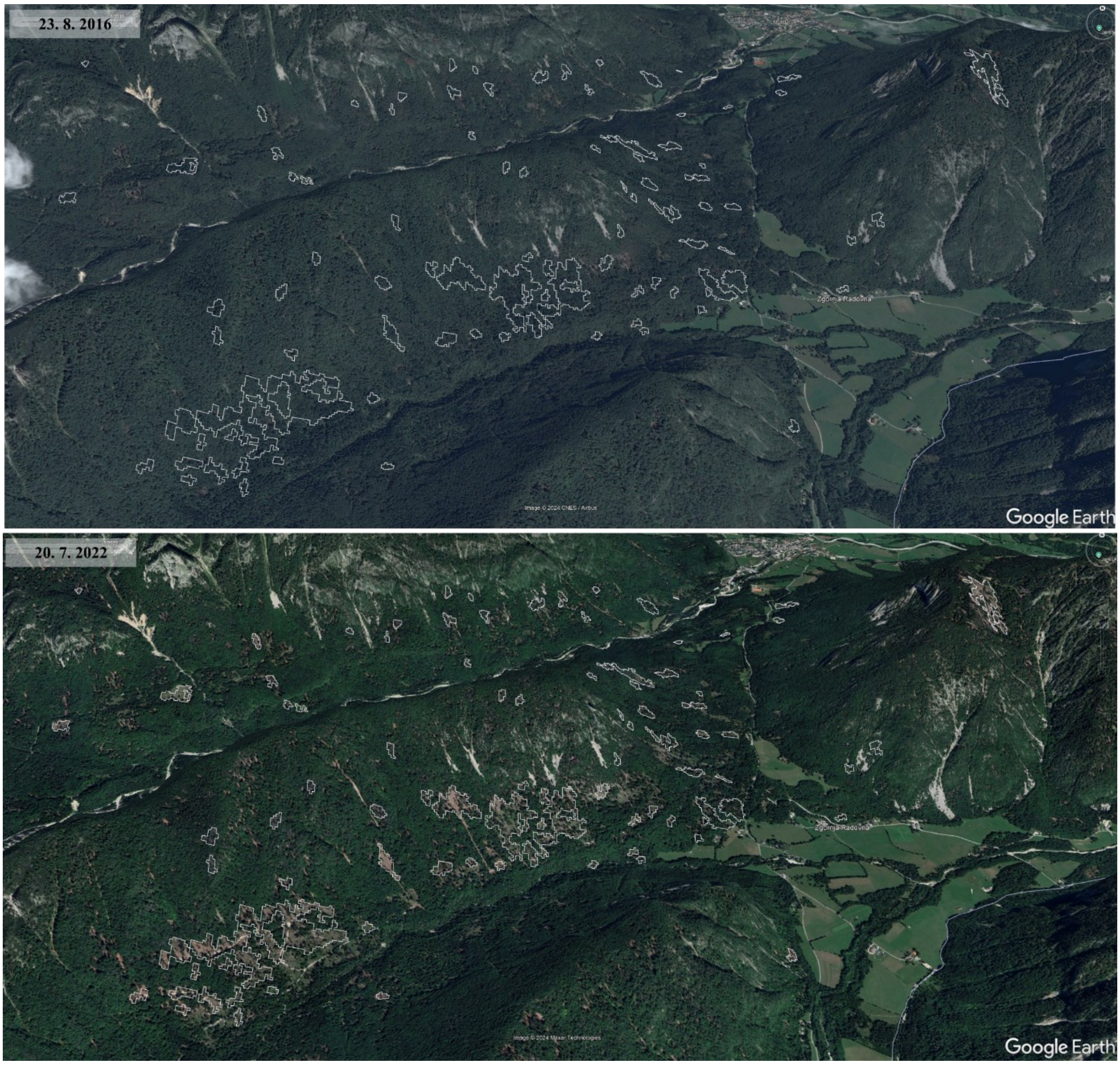

Appendix 1: An extract from the final data set of the bark beetle mask. The first image represents the situation in 2016, while the second image shows the bark beetle area with white polygons. The background is © Google Earth History Arial photos.