

Utilisation of multitemporal SAR data for mapping and statistical analysis of ice and snow breakage of mountainous mixed forest in Bulgaria with Sentinel-1

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Abstract

This study represents analysis of abiotic forest disturbance in mountainous mixed forest, based on change detection and statistical analysis from C-band Synthetic Aperture Radar (SAR) multitemporal SAR data, provided from ESA's Sentinel-1 satellite mission. Statistical means from the backscatter coefficients in both polarisations were calculated, with the dual-pol Radar Vegetation Index ($dRVI$), applying change detection before and after the disaster event. Study period was the summer of 2020 and 2021. The proposed methodology was tested at the Training and Experimental Forest Range of 'Petrohan' hosted by University of Forestry – Sofia. Mean estimates from SAR descriptors with emphasis on $dRVI$ showed high sensitivity to the forest type. The calculated differential orbit-averaged SAR descriptors utilised in change detection analysis, exhibited correlation with the optical Enhanced Vegetation Index 2 (EVI2), with highest sensitivity being the cross-pol Gamma-Nought ($\Delta\gamma_{VH}^0$). The conducted statistical analysis has demonstrated significant differences in backscatter mean values, with the highest sensitivity observed among the three differential SAR descriptors again being the ($\Delta\gamma_{VH}^0$). However, clear identification of the disturbances via SAR descriptors was not possible, primarily due to the mechanism of the disaster event (stem breakage) that resulted in an increased dihedral scattering. Accuracy was also influenced by the geometric distortions due to mountainous relief, which biased the SAR measurements. In conclusion, statistical analysis of multitemporal SAR is well utilised in studying forest disturbances on mixed coniferous mountainous forest. Results suggest need for an *in situ* data and high-resolution quad-pol POL-SAR measurements in a stem breakage disturbed forest.

Key words: forest disturbances, dual-pol RVI, EDUSAR, EVI2, Synthetic Aperture Radar.

Introduction

Forest ecosystems are widely studied by satellite Synthetic Aperture Radar (SAR)

based systems, giving vast of methodological approaches to derive forest biophysical parameters and forest status, in depend on the frequency (Cloude and Pa-

pathanassiou 1998, Fernandez-Ordenez et al. 2009, Le Toan et al. 2011, Caicoya et al. 2012, Kugler et al. 2014). Studying biophysical parameter's diversity via different SAR systems, such as C-band Radarsat-2 and L-band ALOS PALSAR-2 by SAR polarimetry is vital for forest management and deforestation monitoring (Englhart et al. 2011, Stelmaszczuk-Górska et al. 2018). A time series SAR approach by employing Sentinel-1 SAR GRD products were widely assessed for the biophysical parameters estimation, and variation over time (Nasirzadehdizaji et al. 2019).

Forest disturbance plays a key role in forest management, whilst abiotic disturbances¹ could cause a significant gap in the forest canopy (Anev and Marinova 2021). For 2019 the Forest State Agency (FSA) reported that most significant for the disturbances in Bulgarian forests are the biotic factors (e.g. bark beetle and fungal pathogens). Despite that FSA registered a significant increase of the abiotic disturbances for 2022 than 2021 (BNA 2022). The analysis of coniferous forest stands damaged by biotic and abiotic factors established that the abiotic ones are the largest for the stressors ice breakage, followed by snow breakage and the snow uproot (Tonchev et al. 2018). The summary of the databases created in different stages of the project CORINE Land Cover – Bulgaria ascertains that the forested areas in the forest territories of Bulgaria decreased by 67,103.9 ha for the period 1990–2018, which is exactly 2 % of the total forested area in 1990 (Koleva et al. 2019). The abiotic forest disturbances,

such as snowthrow² and icethrow³ are more often investigated by SAR based acquisitions in higher frequencies, such as C-band (Tomppo et al. 2019). That is because the snowthrow as an abiotic disturbance factor at those frequencies leads to significant lowering of the backscatter (Akbari and Solberg, 2022). Disturbances are mostly studied by means of time series approach, by freely available SAR acquisitions from ESA's satellite mission – Sentinel-1. Akbari and Solberg (2022) have found that most of the limitations that bias the results are encompassed in the environmental factors, such as wetness, rainfall, and topography. They recommend a combination of both SAR orbits – ascending and descending to be used to overcome the local incidence angle limitations. Ruiz-Ramos et al. (2020) utilise an approach based on a long time series from Sentinel-1 – Ground Range Detected (GRD) products, to identify clear cuts in Scotland, by reporting the importance of the dual polarization of the SAR data (Ruiz-Ramos et al. 2020). An approach by using change detection between averaged backscatter coefficients from RADARSAT-2 C-band SAR data, is implemented successfully to map selective logging in tropical forests (Antropov et al. 2021). Statistically mean values significantly improve the identification of disturbed forest, before and after the disaster event (Tomppo et al. 2019).

This paper introduces a SAR based method for mountainous disturbed forest

¹ Hereafter, we shall adopt the term 'Abiotic disturbances' to denote the mechanical damages, caused in our case by ice and snow breakage.

² Snowthrow, is braking of branches or even part of the stem caused by heavy wet snow during warm winter, with temperatures around zero. It is a synonym of snow breakage and causes abiotic disturbances.

³ Icethrow – ice breakage in winter.

mapping in rugged terrain, which is implemented for first time by Bulgarian scientists to investigate abiotic forest disturbances. A change detection of approach based on multitemporal SAR data is utilised with statistical mean estimates. The method is based on the Sentinel-1 GRD data products, freely provided by ESA COPERNICUS SAR mission. A comparison between normalised radar cross-section in both polarisations, the dual-pol Radar vegetation index (*dRVI*) and optical (*EVI2*) is made, aiming values differences in disturbed forest stands, before and after the disaster event.

This study represents a pioneering endeavour for Bulgarian environmental sciences, whereas to the best of the authors' knowledge, no comparable investigation has been conducted on the Bulgarian disturbed temperate forests in mountainous regions solely by SAR methods.

The general objective of this investigation is to employ a classical remote sensing approach, exclusively relying on remotely sensed data, for the derivation of specific environmental parameters and status of forest ecosystem. The central hypothesis under scrutiny is the assessment of the suitability and efficacy of time-series analysis by means of Ground Range Detected (GRD) products from ESA's C-band SAR – Sentinel-1, for the mapping, characterisation, and possible identification of abiotic disturbances within mountainous forest.

In that case, the following aims were pursued:

- to implement multitemporal change detection SAR approach, for two reference periods in the summer, employing two acquisition orbits (descending and ascending);

- to calculate the dual-pol Radar Vegetation Index (*dRVI*);

- to calculate statistical mean values in order to eliminate stochastic factors;

- to map mixed forest by means of statistical mean SAR estimates;

- to test a method for identification of forest disturbances in mountainous mixed forest, by means of statistical mean SAR estimates;

- to estimate accuracy and consistency of the used methods.

Data and Methods

Study site

The proposed SAR based methods for forest mapping and disturbances identification was tested in mountainous mixed forest, located at the Training and Experimental Forest Range (TEFR) 'Petrohan', managed by University of Forestry – Sofia. The test site comprises the whole territory, with a total area of 7192 ha situated in the Western Balkan Mountain, north of the capital of Sofia. The forest areas are among the oldest, where its management took place for the first time in 1893 (University of Forestry 2023). The relief is steep mountainous with the lowest point being at 350 m a.s.l., and highest at 1900 m. Most of the territory is steep (about 48 %), where 13 % is very steep. Moderate continental climate is present at the test site. The studied forest is mainly deciduous, where the predominant species is European beech (*Fagus sylvatica* L.) that occupies 82 % of the territory, while the coniferous forest is represented mostly by Scots pine (*Pinus sylvestris* L.) – 5.8 % and Norway spruce (*Picea abies* (L.) H. Karst.) – 4 %.

Forest disturbances registered in TEFR ‘Petrohan’

In January 2021, as a result of microclimatic conditions – thick fog combined with precipitation and a temperature of around 0 °C, damage was caused to the forests. It mainly resulted in branches breakage and stems broken in the middle. The total volume of damaged forests, which are state property managed by University of Forestry, as reported was more than 115,000 m³. The private property forests were not considered. The damaged forest areas are in the altitude range of 550–1000 m, with the largest share of deciduous stands being between 750–950 m. In the areas occupied by coniferous species, a relatively even distribution of the affected areas was observed, predominant areas are established in the range of 650–850 m. In the sake of unavailability of *in situ*, terrain, or aerial measurements it was not possible to assess the fraction of the damaged trees for the entire study area.

A large part (about 80 %) of the forest area, subject of the present study, is located on sloping and steep terrains (11–30 degrees), and this is valid for both coniferous and deciduous forests. Regarding the distribution of the studied area by exposure to the terrain, an approximately equal distribution of the affected coniferous plantations is observed, while areas of shady exposure prevail in the case of broad-leaved ones. Regarding the distribution by age classes, the most areas of plantations between 50 and 60 years were found for coniferous forests, while for broad-leaved forests the largest share of the area is those between 50 and 80, and the data show a relatively small area of forest stands in the range of 100–140 years. It is noteworthy that for the oldest beech stands (>140 years) the share of

the damaged stock of state forests is over 15,000 m³.

Methodology

The methodology is based on a change detection approach solely from C-band SAR, derived from Sentinel-1 SAR acquisitions, where to identify and quantify changes in the forest structure due to disturbances. Its emphasis is on statistical mean estimates of the Gamma-Nought backscatter coefficient before and after the disaster event. It employs the existing differences in backscatter at both cross-pol (VH) and co-pol (VV) polarisations, represented by the normalised radar cross-sections – ‘Gamma-Nought’ (γ_{VH}^0 , γ_{VV}^0). Sentinel-1 dual-polarisation SAR has proven its successful implementation in land cover mapping of the natural scatterers (Abdikan et al. 2016). Polarisation difference is also exploited via the introduced *dRVI* (Trudel et al. 2012, Mandal et al. 2020). Despite utilisation of the different orbit direction, orbit averaged products are also examined (γ_{VH}^0 , γ_{VV}^0 , *dRVI*). The spatial resolution used is 10 m for all SAR products. The considered disaster event is snowthrow that happened in January 2021. Two summer periods with time span from 30th June, till 31st August are considered, for statistical mean estimates – before the disaster event in 2020, and after the disaster event in 2021. SAR data processing was carried out both in ESA Sentinel Application Platform (SNAP), and QGIS.

In this study detailed *in situ* information was not used, because firstly it was unavailable due to lack of terrain measurements, neither any aerial nor visual observation. Thus, it was not reasonable to perform traditional thematic mapping of forest disturbances with concurrent accuracy assessment. Nonetheless, a kind of

such a mapping is performed in terms of testing.

Reference data

As a reference, the forest cadastre with disturbed forest stands is used, preliminary processed from the University of Forestry, Department of Forest Management. For October 2022, the activated stands for sanitary cuts are 132, while the upcoming ones are 69, with the total number of disturbed forests stands at TEFR 'Petrohan', are 201. Percentage ratio from total area is 12.99 %, or 855.9 ha (Fig. 1).

We have no information about any sanitary logging before the summer of

2021. Also, a forest cadastre from the Executive Forest Agency, at TEFR 'Petrohan' is downloaded and processed with software – LESOTEST-2©, in shapefile format, CRS: WGS84 UTM34N. Two classifications are elaborated from the output shapefile, to represent per forest stand the growing stock volume ($\text{m}^3 \cdot \text{ha}^{-1}$), and the mean stand height (or forest volume height – h_v , m). Optical imagery from Sentinel-2 is used as reference, before (acquisition, on 22.06.2020) and after (acquisition, on 27.06.2021) the disaster event, with 20 m spatial resolution. As reference calculated are EVI, and two spectral combinations – NIR-SWIR-Red (B08-B11-B04 on Fig. 2A), and RGB Natural Colours

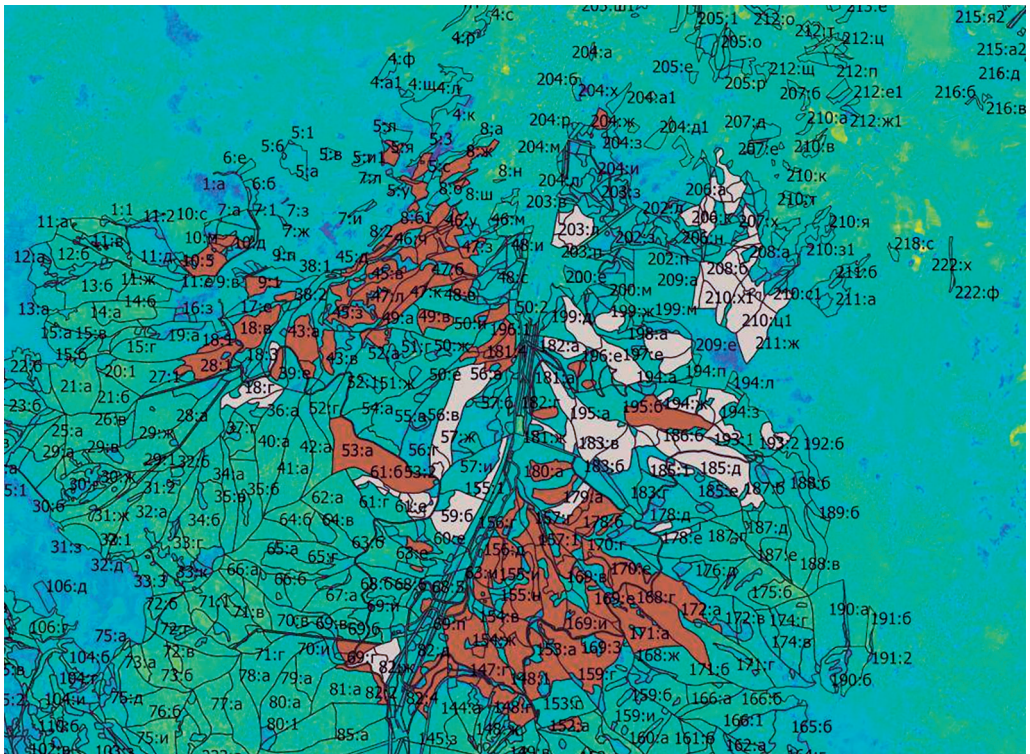


Fig. 1. Activated (brown) and pending (beige) forest stands for sanitary cuts, on disturbed forest cadastre at TEFR 'Petrohan', provided by University of Forestry.

Note: EVI2 index is used to visualise changes in forest structure, calculated from Sentinel-2 acquisition (2021-06-22), after the disaster event.

Sentinel-2 - Natural Colours (B04-B03-B02)

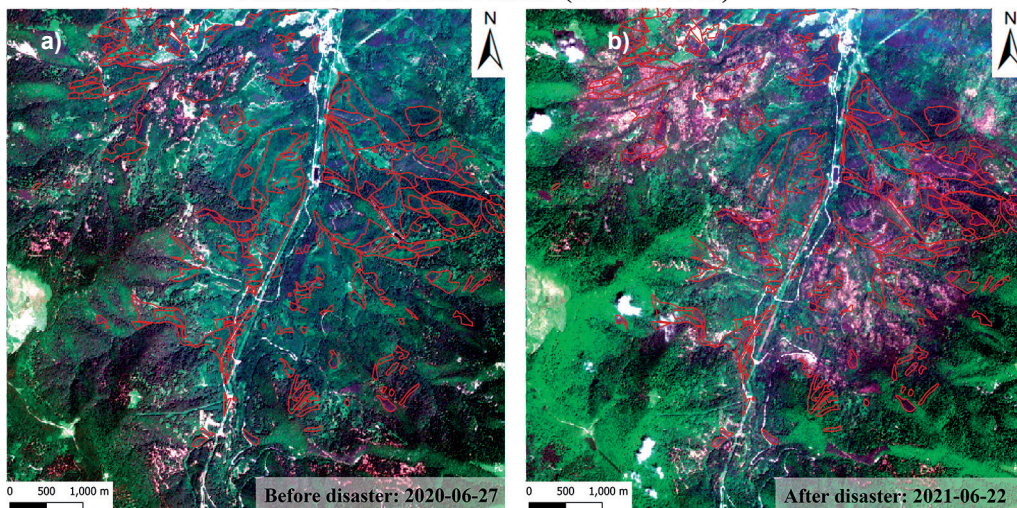


Fig. 2A. Sentinel-2 reference imagery in two band combinations (noted in title), where: a) before disaster – 2020-06-27, b) after disaster – 2020-06-27.

Sentinel-2 - NIR-SWIR-Red (B08-B11-B04)

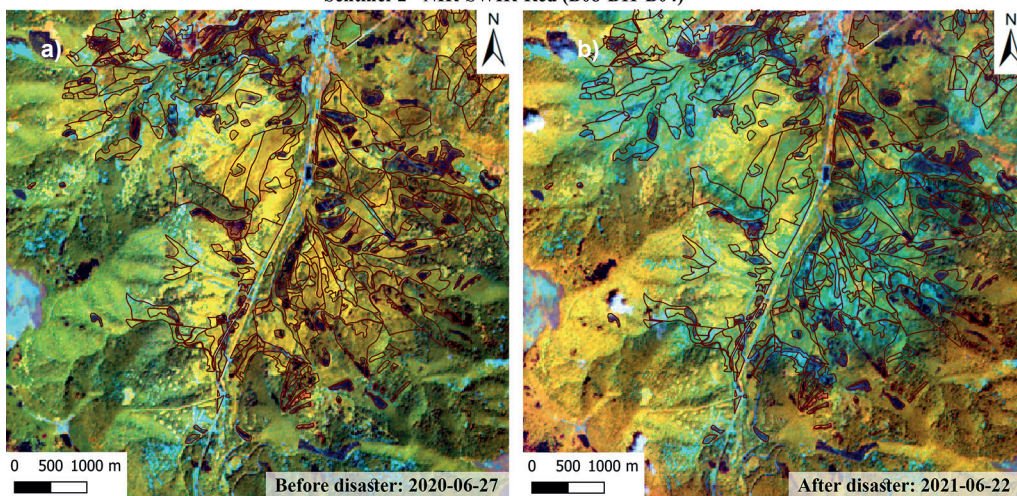


Fig. 2B. Sentinel-2 reference imagery in two band combinations (noted in title), where: a) before disaster – 2020-06-27, b) after the disaster event of snowthrow in the winter 2020/2021.

Note: disturbed forest stands from disturbed forest cadastre are also overlaid in dark red.

(B04-B03-B02, in Fig. 2B).

Copernicus Services HRL 2018 are also used – Dominant Leaf Forest (DLT-2018), and Tree Cover Density (TCD-

2018). The bright colours recognized in Figure 2 are mostly due to reflection from the terrain, rather from the trees. The reason to appear bright in the spectral image

from S2 is that only the stem is left from the whole tree, with no reflection from the leaves. In general, S2 spectral composites are only used to represent changes in the forest before and after the disturbances. On the other hand, EVI2 also takes a major part in the comparison analysis with the SAR observables in the disturbed forest stands.

SAR data processing

Relative Orbit Numbers for GRD products are selected, according to the assumption of an equal incidence angle at the test site. This means that for Ascending this is N29, and for Descending is N80 (Fig. 3).

Twenty scenes were downloaded for

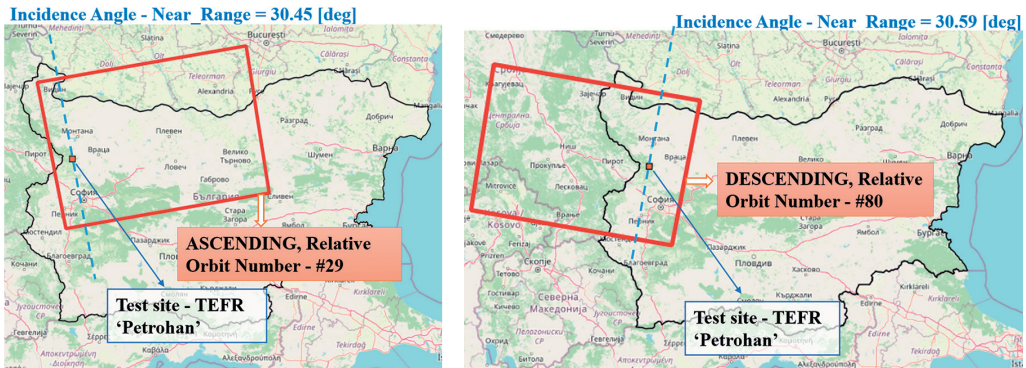


Fig. 3. Relative Orbit Number selection, according to the same incidence angle at the test site, which falls in the near range of both Sentinel-1 orbits (left: ascending, right: descending).

summer periods of 2020 and 2021 obtained by both satellites – Sentinel-1A and Sentinel-1B. In addition, to study geomet-

ric properties during leaf off eight scenes were downloaded, single orbit only, by Sentinel-1A (refer to Table 1).

Table 1. Number of downloaded Sentinel-1 scenes, in ascending (A) and descending (D) orbits, for years 2020 and 2021.

	2020/Before												2021/After											
Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
S-1B							6	4			4	2	2	4					4	6				
S-1A							4	6			2	4	4	2					6	4				
Orbit							A+D	A+D			D	D	D	D					A+D	A+D				
Total							20				4		4						20					

Note: in title rows – greenish points to non-disturbed forest, orange points to disturbed forest after the disaster event; greenish background relates to summer time series, bluish – to winter ones.

The following processing steps are used to elaborate the SAR time series (ESA 2021): import GRD data in ESA SNAP; subset to Area of interest (AOI) of the test site; calibrate to $\gamma_{VV}^0, \gamma_{VH}^0$; Speckle filtering – R. Lee (with window size of

5×5 pixels); convert linear to Decibel (dB); Terrain flattening to remove topography (Small et al. 2010); Geocode by using Range-Doppler; Export to GeoTIFF. Automation is performed via Graph Builder in SNAP (Fig. 4).

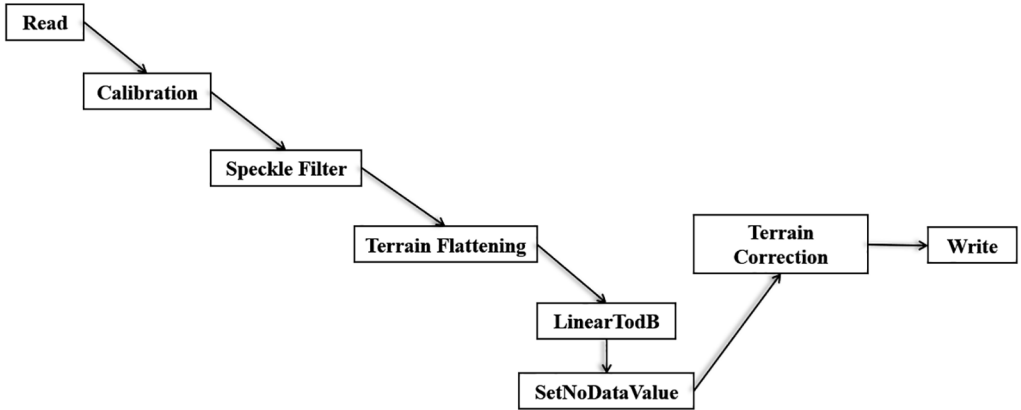


Fig. 4. Processing graph in SNAP.

The reason why Gamma Nought (γ^0) is preferred and used in the methodology instead of Sigma Nought (σ^0), is because γ^0 is a normalised version of σ^0 and therefore it is preferable to be utilised in mountainous rugged terrain. Sigma nought represents the raw radar backscatter coefficient, and its values are influenced by various factors, as variances of the incidence angle from the underlying topography, polarisation, and surface roughness (Abdikan et al. 2016).

During processing different averaging windows in Speckle filtering are tested – 5×5 , 7×7 , and 9×9 pixels. Also, two types of incoherent algorithms are tested – non-adaptive (Boxcar), and adaptive (R. Lee). To preserve the objects geometry – the adaptive one is implemented. As an output a geocoded and terrain flattened Gamma-Nought, for Ascending (ASC) and Descending (DESC) orbits, as well as for co-/cross-polarisations a GeoTIFF files

are produced. The $dRVI$ index is dimensionless, but in purpose of the physical interpretation a conversion of linear values in decibels (dB) is introduced.

Geometric distortions such as foreshortening, in general bias the interpretation of SAR observations. Foreshortening, predominantly occurring at low values of the local incidence angle, is a very common issue in rugged terrain. Consequently, it is imperative to exclude such areas from analysis due to the inherent unreliability of resultant findings.

Results and Discussion

Statistical estimates are calculated via Raster Calculator in QGIS. Also, the $dRVI$ is calculated, per orbit direction, using the formula (Trudel et al. 2012):

$$dRVI = \frac{4\gamma_{VH}^0}{\gamma_{VV}^0 + \gamma_{VH}^0}, \quad (1)$$

where: γ_{VH}^0 – is cross-polarised Gamma-Nought, γ_{VV}^0 – is co-polarised Gamma-Nought.

Coniferous vs broadleaf

A consistency of $dRVI$ with the forest type (coniferous, deciduous) is observed in the

descriptors with the DLT-2018. The reason for this is that the depolarisation of the signal in coniferous forest is much higher than in the deciduous one. This leads to higher response at γ_{VH}^0 , rather than in γ_{VV}^0 . The physics behind is that the coniferous leaves interact more with the polarisation vector of the signal in lower wavelengths, such as C-band (Fig. 5).

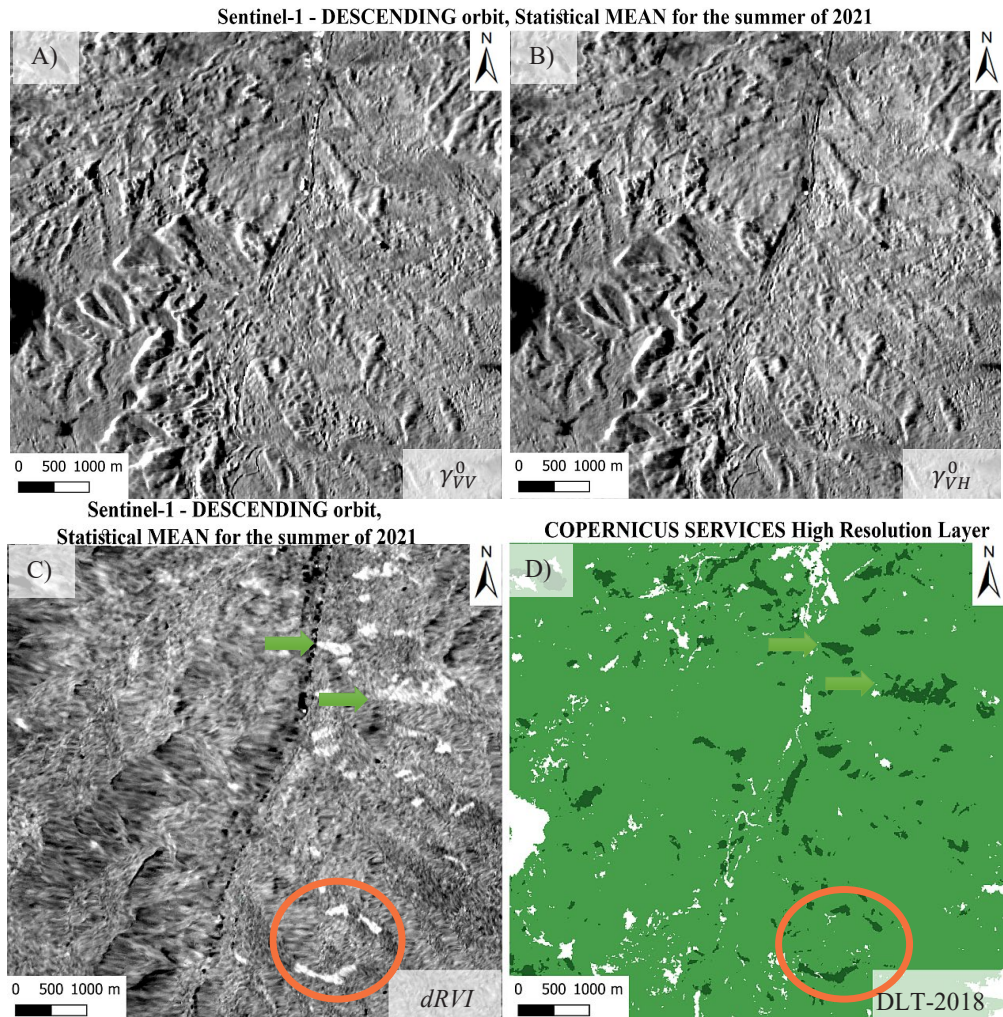


Fig. 5. Three SAR descriptors in DESC – orbit for the summer of 2021, where: A) γ_{VV}^0 , B) γ_{VH}^0 , C) $dRVI$, and D) Dominant Leaf Type for 2018 (DLT-2018).

Note: consistency of $dRVI$ with the forest type is observed, where the white patches found on $dRVI$, match the coniferous forest patches (dark green) on DLT-2018.

This leads to a change of polarisation state and lowering the intensity of the signal. This fact is mostly observed on the polarimetric ratios, such as $dRVI$.

Differences in orbits

The resulting statistical means estimates of the polarimetric products – descriptors are studied for orbit differences. At the backscatter descriptors – γ_{VV}^0 and γ_{VH}^0 the geometric distortions caused by topography (effect of foreshortening) are well recognised but have different imprints and depend on the orbit direction (or the direction to Radar line of sight – RLOS) (Fig. 6).

As reported in other studies here the co-polarised descriptor (γ_{VV}^0) is much more influenced by geometric distortions rather than the cross-polarised (γ_{VH}^0) (Dimitrov 2022). The orbit difference is most obvious on the $dRVI$ descriptor,

where the coniferous forest (see the white patches on Fig. 6) is seen differently on both orbits – Ascending (ASC) and Descending (DESC). This is because of the different orientation of the target vector to the RLOS.

Seasonality differences

A comparison of the different seasonality involving the summer and winter descriptors shows that in winter it is not possible to discriminate coniferous forest from deciduous one, which is obvious on $dRVI$ in both orbits (Fig. 7 – A and C: $dRVI$ in summer; B and D: $dRVI$ in winter).

From Figure 7, it could be concluded that the winter multitemporal does not entail sensitivity to the forest type regarding the summer one. Despite that could be stated that the ascending orbit multitemporal is less influenced by the geometric distortions (i.e. foreshortenings).

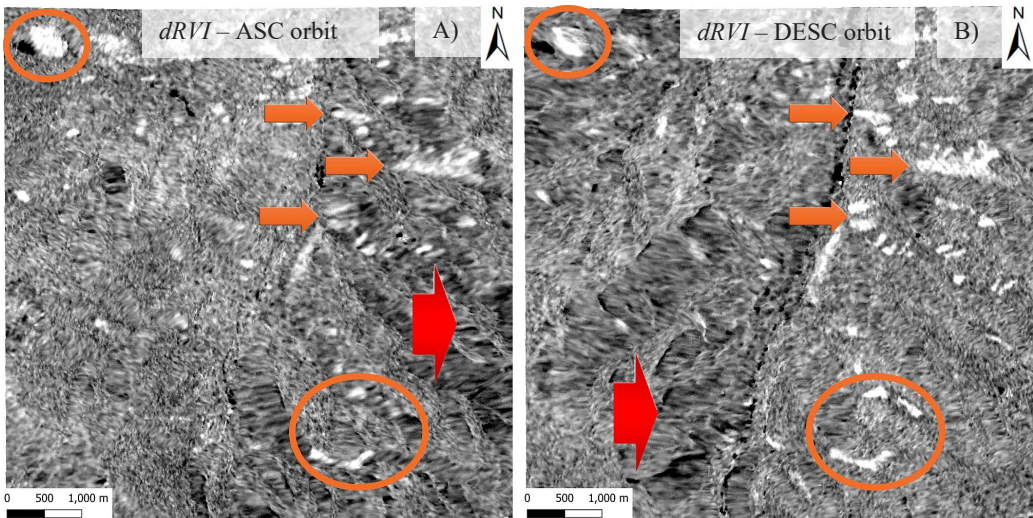


Fig. 6. Comparison of $dRVI$ for the summer of 2021, in – A) DESC orbit, B) ASC orbit.

Note: certain differences are observed, due to different orbit direction, hence the incidence angle and position of the target vector to the RLOS.

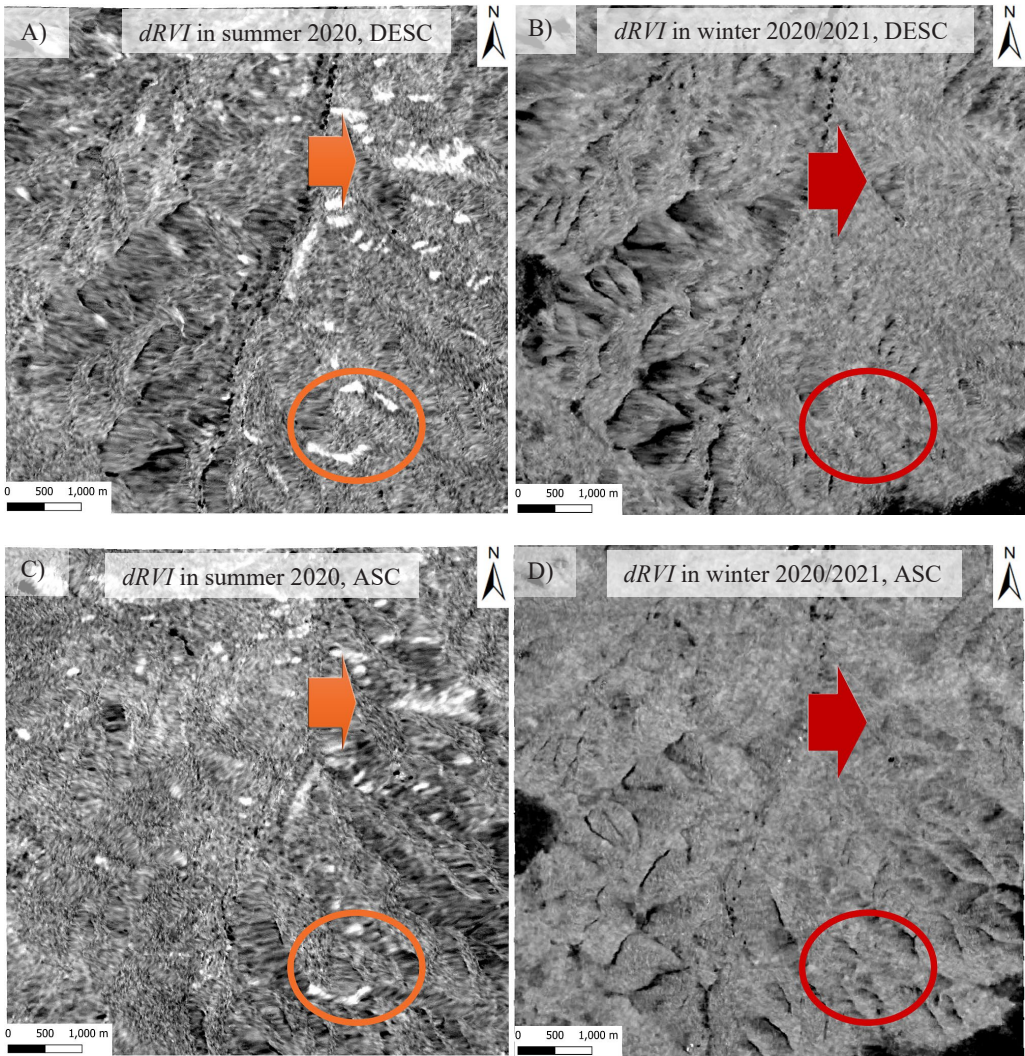


Fig. 7. Comparison of different seasonality, where: A) $dRVI$ for the summer of 2020 in DESC orbit, and C) same for ASC orbit; B) $dRVI$ for the winter of 2020/2021 in DESC orbit, and D) same for ASC orbit.

Note: Please, note that on the summer multitemporal mean (A and C), the forest type is indicated, where white spots represent the coniferous forest. Despite that the winter multitemporal mean (B and D) does NOT entail such a sensitivity. One of the reasons why the summer multitemporal is preferable.

Orbit averaging

Following the recommendation outlined in the study of Akbari and Solberg (2020) an orbit averaging is performed for the sum-

mer seasons only, by using the formulas (2, 3, and 4):

$$\overline{\gamma_{VH}^0} = \frac{\gamma_{VH}^{0 \text{ ASC}} + \gamma_{VH}^{0 \text{ DESC}}}{2}, \quad (2)$$

$$\overline{\gamma_{VV}^0} = \frac{\gamma_{VV}^{0\text{ASC}} + \gamma_{VV}^{0\text{DESC}}}{2}, \quad (3)$$

$$\overline{dRVI} = \frac{dRVI^{\text{ASC}} + dRVI^{\text{DESC}}}{2}, \quad (4)$$

where: *ASC* – descriptors are in ascending orbit; *DESC* – descriptors are in descending orbit.

Therefore, the geometric distortions are slightly diminished with a smaller impact on the descriptors. Backscatter intensities are less biased from the speckle effect, which leads to a smooth improvement regarding the separate orbits.

Differential layers

To complete the analysis a computation of layer differencing (or, differenced descriptors), by math subtraction are calculated, aiming the orbit averaged ones for summer of 2020 (before), and for summer of 2021 (after). The produced four differenced descriptors – $\Delta EVI2$, $\Delta \gamma_{VV}^0$, $\Delta \gamma_{VH}^0$, $\Delta dRVI$ are examined in QGIS with disturbed forest cadastre overlaid. Negative values are considered, due to the assumption that the backscatter BEFORE is higher, than after the disaster event (Akbari and Solberg 2020, Antropov et al. 2021). This is especially true at the cross-polarised differenced descriptor, because of the diminished volume backscatter in the rest understory and low vegetation. In this regard, the backscatter at the disturbed forest stands is observed to be higher in the co-pol $\Delta \gamma_{VV}^0$, rather than the cross-pol $\Delta \gamma_{VH}^0$.

Forest disturbances analysis with SAR and optical data

In the analysis the disturbed forest cadastre is used, provided by the University of

Forestry, Department of Forest Management. The disturbed forest cadastre was overlaid with the optical EVI2 layer differencing (differenced descriptor – $\Delta EVI2$), from the summer of 2020 and 2021, but also the SAR differenced descriptors – $\Delta \gamma_{VV}^0$, $\Delta \gamma_{VH}^0$, $\Delta dRVI$.

Therefore, the $\Delta EVI2$ negative values should be clearly related to the possible forest loss, due to lack of vegetation in the post-disaster period in the summer of 2021. Instead, dark values (negative pixels) are also found away from the disturbed forest stands, which is embarrassing. Reanalysis showed bias from environmental factors that considers opposite slopes with North aspect that leads to low irradiation fluxes from the Sun, and differences in woods growth altitude. This had led to specification of the wood's development in those areas and therefore lowered the values of EVI2 at the time of S2 acquisition in the summer of 2021.

This leads to the conclusion that $\Delta EVI2$'s negative values could not be solely used for identification of the disturbed forest in our case (Fig. 8).

As observed from Figure 8 the negative values of SAR differenced layers (differenced descriptors) $\Delta EVI2$ and $\Delta \gamma_{VH}^0$, does not fully identify as expected damaged woods, where negative values in bluish does not completely correlate with the disturbed forest stands boundaries in red-dish. Must be stated that the Figure 8 has representative character about the layer differencing results only, therefore it does not represent identification results of actual snow and ice damages. The other two $\Delta \gamma_{VV}^0$ and $\Delta dRVI$ are less representative and does not visually represent changes. This is discussed in the statistical analysis later, aiming how much they correlate with $\Delta EVI2$.

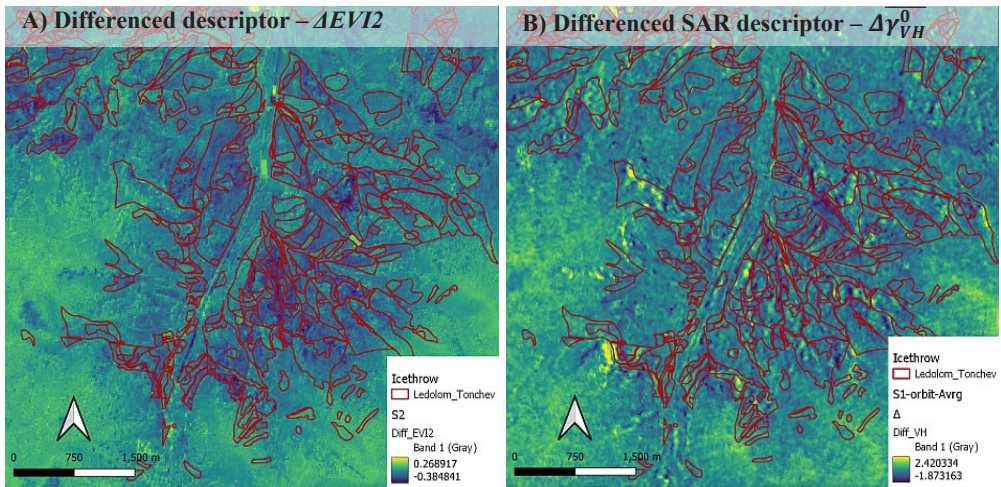


Fig. 8. Layer differencing results (or, differenced SAR descriptors), with overlaid disturbed forest cadastre (in dark reddish), where: A) $\Delta EVI2$, B) $\Delta \gamma_{VH}^0$.

Comparison of the differenced descriptors showed that SAR ones are less sensitive to the differences in forest changes, rather than $\Delta EVI2$. This arises an important question why we observe such a result? One of the answers given is related with the specifics of the snow and ice breakage. On Figure 9 are represented the damaged woods, where stem breakage is present in general, but mixed with undamaged standing trees also! This leads into two things: 1) much lower index values in $EVI2$ after disturbances, which also

lead to a higher negative value observed in $\Delta EVI2$, because the lack of crowns with needles that hold the chlorophyll; 2) small differences in the SAR backscatter before and after the disaster event, where after the disaster higher dihedral with surface scattering almost replaces volume scattering before the disaster event. This is why in this snow/ice breakage, it could not be solely stated that SAR differenced descriptors are more sensitive to the forest change, in respect to the optical one (Fig. 9).

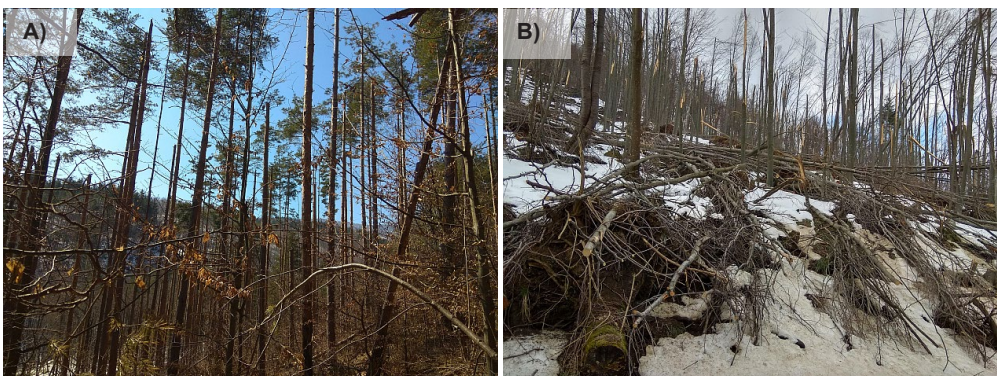


Fig. 9. Two disturbed forest stands, both having stem breakage that is mainly observed as a common breakage type at test area, where: A) young conifers, B) young beech.

relates, mostly with the cross-pol – $\overline{\Delta\gamma_{VH}^0}$ and least with the $\overline{\Delta dRVI}$ (Table 2). The last could be true, because the cross-pol channel (VH) is clearly more sensitive to the forest volume rather than the co-pol and $dRVI$.

Applying zonal statistics instruments via ArcGIS, represents the mean-value changes across disturbed and non-disturbed forest stands, by statistically averaged values. Except the $\overline{\Delta\gamma_{VV}^0}$ whole mean values at disturbed forest stands from the difference layers are negative, whilst at the non-disturbed forest stands those are positives. Regarding SAR data the highest change is observed at the $\overline{\Delta\gamma_{VH}^0}$ (more than 0.2), while $\overline{\Delta dRVI}$ certainly changes its sign. Positive changes observed at non-disturbed forest stands should be correlated with the forest environmental factors changes. Forest regrowth for one year is too small to be a reason.

The ANOVA test, performed on the mean values of the six SAR data series – $\overline{\gamma_{VV}^0}$, $\overline{\gamma_{VH}^0}$, $\overline{dRVI}$ from both summer periods (i.e. 2020 and 2021), is applied to measure similarities in between. In addition, correlation and covariance are also calculated to those data series. The results showed that for both summer periods the $\overline{dRVI}$ differs more than the – $\overline{\gamma_{VH}^0}$ and $\overline{\gamma_{VV}^0}$. This is confirmed also on the covariance estimation of both series of $\overline{dRVI}$ (see Table 3). Correlations between series from both years show relatively low correlation in between, where differences should be due to environmental changes that influenced both summer periods, but also the forest disturbances.

Looking for a certain indication at the differenced SAR descriptors (i.e. $\overline{\Delta EVI2}$, $\overline{\Delta\gamma_{VV}^0}$, $\overline{\Delta\gamma_{VH}^0}$, $\overline{\Delta dRVI}$), separation of disturbed from non-disturbed forest stands is performed, by using the available for-

est cadastre layers. Implementing zonal statistical tools in ArcGIS®, average values (mean estimates) are calculated for the differenced SAR descriptors. This showed certain differences for disturbed and non-disturbed forest stands (Fig. 9). Looking at the disturbed forest, values of the differenced SAR descriptors are much lower, rather than those representing the healthy forest. Highest sensitivity to the disturbed forest is found in the changes of mean of the cross-pol difference SAR descriptor – $\text{Mean } \overline{\Delta\gamma_{VH}^0}$. Observed change is with more than 0.23 dB in respect to the co-pol – $\text{Mean } \overline{\Delta\gamma_{VV}^0}$, which also shows higher change. This leads to clear identification of forest disturbances, leading to physical changes of forest geometry (Fig. 11).

From both graphs on Figure 11 it could be concluded that a certain difference is observed between disturbed forest stands (on A) and non-disturbed (on B). This is a certain indication of the snow/ice breakage (resulted from the snowthrow and ice-throw disaster events) of the forest causing abiotic stress. Besides, the SAR differenced descriptors are showing sensitivity to this change, where more sensible is the backscatter (i.e. $\overline{\Delta\gamma_{VV}^0}$ and $\overline{\Delta\gamma_{VH}^0}$), rather than the $\overline{\Delta dRVI}$. To point out the magnitude of those differences a subtraction is made of mean-estimates without forest disturbances (i.e. MEAN NonDisturbed) from the disturbed ones (i.e. MEAN Disturbed) (Table 4), from which it is seen that actually most sensitive SAR descriptor is namely $\overline{\Delta\gamma_{VH}^0}$.

Notably from Figure 11, only $\text{Mean } \overline{\Delta EVI2}$ shows negative value changes in the disturbed forest area in respect to the non-disturbed one, which is negative but very close to zero. To study these differences a division is performed on broadleaf

Table 2. Correlation results from differenced descriptors from Sentinel-1 and Sentinel-2.

Coefficient of determination	$\Delta EVI2 \sim \Delta \overline{\gamma_{VH}^0}$	$\Delta EVI2 \sim \Delta \overline{\gamma_{VV}^0}$	$\Delta EVI2 \sim \Delta \overline{dRVI}$
<i>R</i>	0.4547	0.3436	0.2167

Note: the backscatter in both polarisations only shows some degree of similarity with the $-\Delta EVI2$.

Table 3. Statistical accuracy estimation – ANOVA, correlation, and covariance, on series for both summer periods that constitutes from mean orbit averaged SAR descriptors.

Applied test	$\overline{dRVI}$	$\overline{\gamma_{VH}^0}$	$\overline{\gamma_{VV}^0}$
ANOVA	77.963	50.927	54.050
Correlation	0.7706	0.7597	0.7275
Covariance	0.2092	0.1335	0.1377

Note: tests are applied over both series from summer of 2020 and summer of 2021.

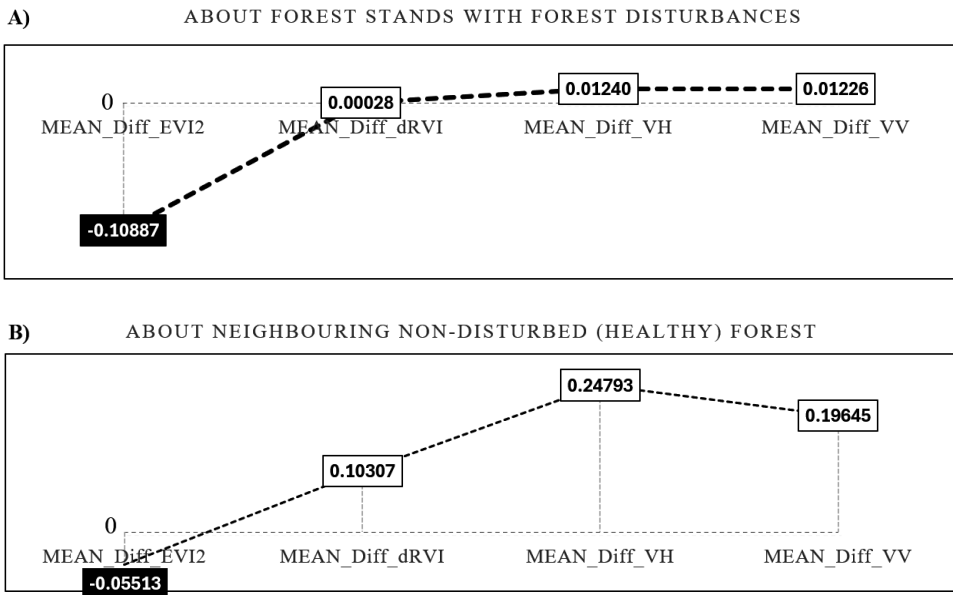


Fig. 11. Mean values of the differenced SAR descriptors and optical EVI2, statistically averaged over forest stands, where: A) Forest stands with disturbances caused from the icethrow disaster event; B) Non-disturbed (or healthy) forest stands nearby.

Note: Negative values are with black background. Differenced descriptors ($\Delta EVI2$) and their mean values from zonal statistics are noted as: MEAN_Diff_EVI2, MEAN_Diff_VV, MEAN_Diff_VH, Mean_Diff_dRVI.

Table 4. Computed differences of the statistically averaged over forest stands mean values of the differenced descriptors, between those with forest disturbances from those without.

Δ MEAN	MEAN_Diff_EVI2	MEAN_Diff_dRVI	MEAN_Diff_VH	MEAN_Diff_VV
MEAN Disturbed – MEAN NonDisturbed	-0.05374	-0.10280	-0.23553	-0.18419

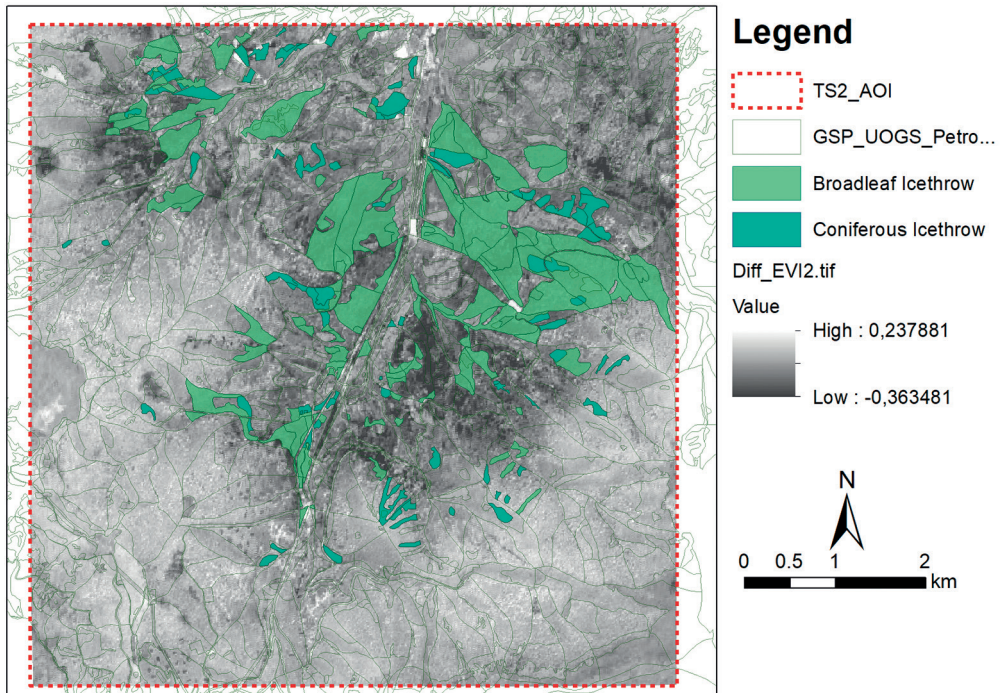


Fig. 12. Disturbed forest stands are divided by forest type in GIS.

versus coniferous forest stands (Fig. 12).

Thus, disturbed forest stands are divided by forest type in GIS, where 142 forest stands resulted as broadleaf, and 93 as coniferous ones (Fig.12). The next statistics utilises mean estimates per forest stand derived from zonal statistics in ArcGIS, from the orbit averaged SAR descriptors, or $\overline{dRVI}$, γ_{VH}^0 , γ_{VV}^0 , for both summer periods of 2020 and 2021. The overall statistical means are calculated, denoted again as – $\text{Mean}_{\overline{dRVI}}$, $\text{Mean}_{\gamma_{VH}^0}$ and $\text{Mean}_{\gamma_{VV}^0}$, for both forest types and summer periods (Table 5).

Highest differences are observed at $\text{Mean}_{\overline{dRVI}}$ showing lower depolarisation of the signal in post-disaster period, with notable positive values for coniferous forest at both periods. This is because coniferous forest exhibits higher depolarisation of the signal than the broadleaf one. It seems that differences between both periods for the backscatter are very low, with maximum difference of 0.054 for the $\text{Mean}_{\gamma_{VH}^0}$ in coniferous forest. Influence from geometric distortions may influence those low differences in between. This leads to conclusion that $\overline{dRVI}$ show

Table 5. Statistics for both summer periods, of the three SAR descriptors, in respect to the forest type, from disturbed forest stands.

Mean estimates	Mean $\overline{dRVI}$		Mean $\overline{\gamma_{VH}^0}$		Mean $\overline{\gamma_{VH}^0}$	
Summer periods	Broadleaf	Coniferous	Broadleaf	Coniferous	Broadleaf	Coniferous
Summer 2020	-0.7851	0.3840	-13.506	-13.235	-7.093	-7.406
Summer 2021	-0.6199	0.2275	-13.477	-13.262	-7.147	-7.355

better sensitivity to changes in the structure of the forest, with better delineation on forest type. Hereafter, the elaborated boxplots derived from the zonal statistics in ArcGIS in the above visually represent the statistical distributions and mean values change, before and after the disaster event (Fig. 13).

Due to the highest difference is for $dRVI$ it is shown only in the figure. Statistics for $\overline{\gamma_{VH}^0}$ and $\overline{\gamma_{VV}^0}$ are overlapping for both periods and are not representative for the forest change. The boxplots are not so much representative for the forest change, despite that mean values differ. This is related with the already discussed fact that before and after the disaster event, the backscatter is high in the dam-

aged forest stands. Nonetheless, changes are observed in between. Also, the geometric distortions also introduce higher backscatter and bias the interpretation.

As a final, the following statistics are calculated aiming to study dependencies in age of the forest species. Analysis is based on the disturbed forest cadastre and the estimated mean values of the differenced SAR descriptors (i.e. Mean $\overline{\Delta\gamma_{VH}^0}$ and Mean $\overline{\Delta\gamma_{VV}^0}$) (Fig. 14).

Results showed higher value diversity of Mean $\overline{\Delta\gamma_{VH}^0}$, in respect to the forest age, having an outlier at the age of 120, where value is 0.584. The reason could be due to geometric distortions, which could strongly bias the values of the Mean $\overline{\Delta\gamma_{VH}^0}$ in a mountainous region. Nonetheless, SAR

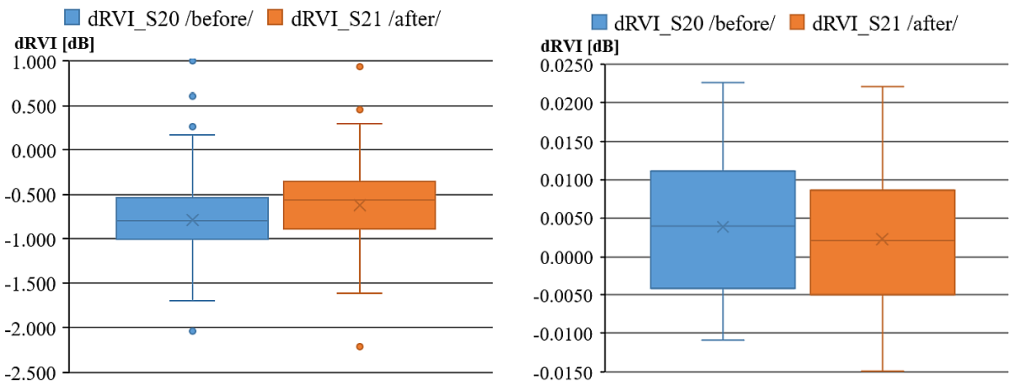


Fig. 13. Statistical analysis of time series data conducted for the summer periods of 2020 (pre-disaster) and 2021 (post-disaster) for $dRVI$, with particular attention to variations across different forest types, such as coniferous (left) and broadleaf (right) forests.

Note: pre-disaster period is in bluish, posts-disaster period is in orange.

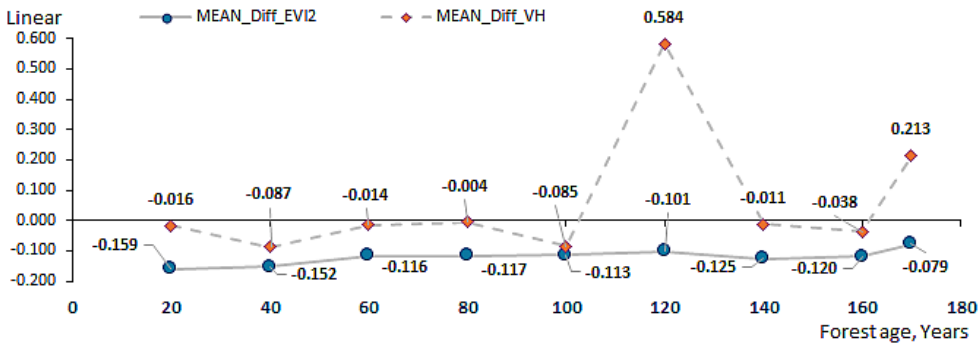


Fig. 14. Mean values change in respect to the forest age, for $\Delta\gamma_{VH}^0$ (Mean_Diff_VH), and $\Delta EVI2$ (Mean_Diff_EV12).

Note: for the purpose of comparability both $\Delta\gamma_{VH}^0$ and $\Delta EVI2$ are represented in linear values.

is much more sensitive to the geometry of forest and therefore could be pointed out that $\text{Mean}_{\Delta\gamma_{VH}^0}$ is more sensitive to the dependency of forest age, than $\text{Mean}_{\Delta EVI2}$.

Conclusions

In this study a large-scale forest mapping and statistical analysis, by employing a C-band Synthetic aperture radar (SAR) multitemporal approach was performed, proving that ESA's Sentinel-1 is fully capable to distinguish forest type and geometry changes of the forest canopy.

This sensitivity plays a key role in studying forest disturbances in temperate forest located in rugged terrain. Study is held in a complex forest structure, such as Bulgarian mountainous forest in TEFR 'Petrohan', of University of Forestry, by means of mean estimates from multitemporal SAR acquisitions (or, SAR descriptors) in both orbit directions – ascending and descending (i.e., γ_{VH}^0 , γ_{VV}^0 , $dRVI$). A change detection approach is held, by referencing summer periods before the disaster in 2020 and after snow and ice breakage in the summer of 2021, show-

ing high utilisation value of the mean estimates. In this manner the SAR descriptors represents highest possible centre of mass of the scattering centres, besides this approach fully determine the forest type, and almost fully correlates (i.e. $r^2 > 0.91$) with the reference layer from COPERNICUS HRL Dominant Leaf Type (DLT-2018).

Utilisation of the mean SAR descriptors is made by referring to the optical index (EVI2). The differenced SAR descriptors ($\Delta dRVI$, $\Delta\gamma_{VH}^0$, $\Delta\gamma_{VV}^0$), and the differenced optical one ($\Delta EVI2$), showed certain changes in forest structure within disturbed forest, apart from the non-disturbed one. Statistical analysis showed that highest change is observed at $\text{Mean}_{\Delta\gamma_{VH}^0}$ and $\Delta EVI2$, whereas most meaningful differenced layer is $\Delta dRVI$. Changes in coniferous forest were most significant at the $dRVI$ apart from the backscatter (i.e., γ_{VH}^0 and γ_{VV}^0). It could be concluded that in general $dRVI$ shows better sensitivity to changes in the structure of the forest, with better delineation on forest type. It could be stated that to study complex temperate forests in mountainous regions by means of Sentinel-1

SAR data and methods, the methodology should rely on statistical mean estimations in dual polarimetry (VV and VH). This approach overcomes the stochastic factors, speckle, and geometrical distortions that accompany SAR measurements.

It must be noted that the GRD data products are slightly unreliable for the purpose of the study. Improvement should be made with the SLC data products that hold the original speckle pattern per each pixel, representing the original geometry of the backscatter process. Further research will include a dual-pol special case (i.e. HH+VV), or fully polarimetric data (i.e. HH+VV+HV), to fully represent the snow/ice breakage via POL-SAR data.

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