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Assessment of the Risk of Disturbance Impact on Primeval and Managed Forests Based on Earth Observation Data Using the Example of Slovak Eastern Carpathians

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ABSTRACT Forests of Slovak Eastern Carpathians provide essential services to society ensuring human well-being. Primeval forests that remained there untouched have exceptional value. Unsustainable logging and climate change intensify forest disturbances and may cause substantial forest loss. The engagement of remote sensing allows timely monitoring and prediction of negative consequences. The leaf area index is selected from the other forest's condition indicators to assess the forests' quantity and disturbance. The conceptual approach for risk assessment of forest disturbance is proposed. This approach uses multiscale multi-temporal Earth observation data, such as synthetic aperture radar imagery and high-level satellite data products. The output response of the forest's condition was restored by multivariate regression with radar backscattering coefficients, relative difference polarization index, and local incidence angle. The low-resolution leaf area index pre-developed Copernicus data products make it possible to characterize the forest's condition without ground truth measurements. According to the elaborated methodology, a time series of the leaf area index was mapped, and risks analysis was performed according to hazard functions. A resulting risk's gradations map is a good tool for future research and decision-making support in nature management. The high spatial resolution of the output maps allows getting a more detailed assessment of forest disturbance behavior.

INDEX TERMS Earth observation, forest disturbance, leaf area index, optical/radar imaging, relative difference polarization index, risk assessment, Slovak Eastern Carpathians, time series analysis.

I. INTRODUCTION

Forests are an essential element of the biosphere that maintains its natural cycles and resilience. Providing both tangible and intangible services to society, ranging from the production of raw materials, climate and water flows regulation to the protection of soils and biodiversity conservation, they ensure human well-being [1].

In this respect, beech forests, typical in the Carpathians, represent one of the most significant forest types of the northern hemisphere Temperate Broadleaf Forest Biome [2]. They are also referred to as primary, virgin or ancient forests that have developed for a long time without significant human intervention [3]. Primeval forests are characterized by complex vertical and horizontal structures, the features that are usually missing or rare in managed or plantation forests [4]. That makes primeval forests highly valuable for supporting significant biodiversity [5], storing and sequestering large amounts of carbon [6], and buffering microclimate [3].

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Since 2007, 10 protected areas with the Primeval Beech Forests of Carpathians (Slovakia, Ukraine) have been on UNESCO's World Heritage List [7].

In Slovakia, as in many human-dominated regions, most forests are currently managed, often with a tendency to lose due to high demand for timber [7], [8]. Unsustainable logging is considered the main threat for both managed and primeval forests in the country [7], [9]. Forest disturbances, as well, are sensitive to climate. However, the understanding of disturbance dynamics in response to climatic changes remains incomplete [10].

Forest disturbance is defined as a relatively discrete event causing a change in the environment's physical structure, composition, and functional processes [11]. In forests, disturbance can result from natural processes (wildfires, severe windstorms, flooding, insect outbreaks, disease affections, landslides, and avalanches) or human activity (land conversion, logging, and mining). Also, forest disturbance has a wide temporal range, from abrupt events to a chronic and broad spatial extent, from large to small [12]. Usually, forest disturbance is associated with a loss of aboveground biomass and structure disruption [13].

Monitoring and control of forest structure are essential tools for understanding disturbance processes as the drivers of forest degradation [14], and thus are important for the restoration of forests, especially reserved ones [15]. There are different technologies based on Earth observation (EO) data from passive or active sensors to monitor a forest canopy structure [16], [17]. They are widely used in forest disturbance research [12], [18] and becoming more involved in exploring the disturbance of primeval forests [4], [19]. Significant advances in tracking changes in forest structure have been associated with the free archive of Landsat imagery [20]. Distortions in canopy structure can be detected between pairs of images (bi-temporal) as well as between time profiles of imagery-derived indicators (temporal trajectories) [21]. Unlike the bi-temporal comparison indicating only whether the change has occurred, time series algorithms utilize the mass-processing of Landsat satellite imagery, capable of detecting trends in forest disturbance and recovery [22], [23]. In these studies, forest disturbance mapping is based on optical remotely sensed imagery and employs different vegetation indices to reveal the changes in canopy structure [14]. One of these indices is *Leaf Area Index* (LAI) which we propose to use in this study for the development of risk's maps of forests.

LAI is considered to be superior to vegetation indices since it is a three-dimensional parameter of the vegetation canopy [24]. LAI is often used as a basic descriptor of local vegetation structure for comparisons among systems [25]. LAI is one of the essential variables known to be critical for observing and monitoring a given facet of the Earth system (https://earthdata.nasa.gov/learn/backgrounders/essential-variables). Nevertheless, LAI remains one of the most difficult parameters to quantify properly due to its large spatial and temporal variability.

Over the past two decades, several global LAI based products have been generated. LAI estimation algorithms provide high (4-16 days) temporal and moderate (250 m - 7 km) spatial resolution products from current satellite missions [26]. Among the main LAI products with spatial resolution up to 500m can be mentioned: 1) Moderate Resolution Imaging Spectroradiometer (MODIS) Level 4, LAI 500 m product, 2) LAI 300m Version 1 product by PROBA-V satellite system provided by the Copernicus Global Land Service, and 3) the LAI Collection 300m Version 1.1 product, based on Sentinel-3/OLCI data. These products have good precision and smooth temporal profiles [27] but do not always provide full coverage and good seasonal repeatability due to cloudiness.

Active remote sensing instruments (LiDAR in the visible/NIR and SAR in the microwave) [12] are generally more directly sensitive to forest canopy biomass (microwave) and canopy height and vertical biomass distribution (LiDAR and InSAR) than passive solar reflectance instruments (multi- and hyperspectral optical sensors). Nevertheless, active remote sensing techniques also have shortcomings, like a cloud or smoke interference for LiDAR or biomass saturation for radar [28], [29].

Most studies devoted to LAI mapping from C-band SAR were conducted for boreal forests [30], [31]. The main data sources in such cases were previous-generation SARs of ERS and Envisat satellites. Novel Sentinel-1SAR data, provided by Copernicus Open Access Center, are increasingly being used for both LAI [32] and forest disturbance mapping, including quantitative assessment of short-term forest disturbance [33].

Due to the radio shadows occurring in radar surveys of areas with complex terrain, applying topographical adjustments for mountain forest LAI estimations has critical importance [32].

In this study, we propose a new general approach to provide a risk assessment of forest disturbance based on multisource and multiscale EO data time series. The proposed approach synthesizes three unified methodologies: multiscale remotely sensed data processing, multivariate regression analysis, and the time series risk trend extraction. Each of the used methodologies in isolation is known and well described [9], [12], [15], [20], [21], [28], [34]–[38], but together they provide useful synergy for satellite risk mapping under the absence or insufficient amount of ground truth data. Although risk assessment is quite successfully applied for forest landscape degradation trends [34]–[38], risk analysis of forest disturbance is still rare. In this study, the proposed approach was applied to the primeval and managed forests of Slovak Eastern Carpathians.

Using the proposed approach, we assessed the risk of forest disturbance and visualized it by maps. Furthermore, the approach ensured: (1) to explore the potential of using well-verified LAI products of low spatial resolution and radar satellite imagery of high resolution to estimate forest LAI in the rugged terrain of mountains; (2) to detect changes in forest canopy structure from LAI time series; (3) to introduce the approach for risk assessment of forest disturbance.

The paper is structured as follows. Section II introduced the investigated area and its specifics. The main steps of the proposed approach are considered in section III. The data for risk evaluation and the methods (algorithms) for high resolution and risk evaluation are discussed in section III too. Section IV shows the map of forest disturbance risk. The evaluation and analysis of the proposed approach are discussed in section V.

II. STUDY AREA

The study area is in northeastern Slovakia and belongs to the Eastern Carpathians (Fig.1, upper panel). This area is of particular concern for disturbance assessment as a recognized biodiversity hotspot within the European temperate zone [2], [19]. The beech forests added to UNESCO's World Heritage List are situated here in strictly protected nature reserves [7]. Poloniny National Park and Vihorlat Protected Landscape Area contain nearly homogenous, largely monodominant mature beech forests and the tallest and largest European beech specimens in the world. The hillsides of Eastern Carpathians, 500–1221 m.a.s.l., are home to primeval beech forests of all developmental stages [39].

We identified the forest cover of the area of interest (Fig.1, lower panel) based on the European forest area map at 100m spatial resolution covering EEA39 in 2015 (https://discomap.eea.europa.eu). The virgin forest inventory data set provided by the European Environmental Agency [40] and the profile for Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe from the World Database of Protected Areas [41] was used to distinguish the distribution of primeval beech stands.

However, as for some other components of the World Heritage site, in Slovakia, high demand for timber remains the main negative driver of forest disturbances. The Poloniny National Park was under serious pressure from unsustainable logging at 93% of its area, as the expert mission of the Council of Europe stated [7].

The application of the developed approach to the analysis of primeval and managed forests in the Slovak Eastern Carpathians, we also address the questions:

- What is the rate of forest disturbance risk within the primeval forests in the Slovak Eastern Carpathians?
- How does the rate of forest disturbance risk vary across the primeval and managed forests?
- Do Protected Areas (PAs) influence the rates of forest disturbance?

III. APPROACH FOR RISK ASSESSMENT OF FOREST DISTURBANCE

A. APPROACH CONCEPTION

There are many methods for multiresolution data processing, ranging from the most straightforward interpolation to logical reallocation of spectra for multispectral data [42] or subpixel superresolution for dual polarisation radar data [43]. In this study, a non-trivial task was posed–to map LAI by high-resolution dual polarisation radar data without ground truth measurements. In this case, the remotely sensed verification data are needed, but available ones are only of low resolution, as the introduction says. That means that to solve the problem that occurred, it is necessary to: a) develop a technique for the multiresolution data fusion of both radar imaging and LAI product, b) improve a previously used method for LAI acquisition using dual polarisation radar data, c) adapt the elaborated methodology to risk analysis.

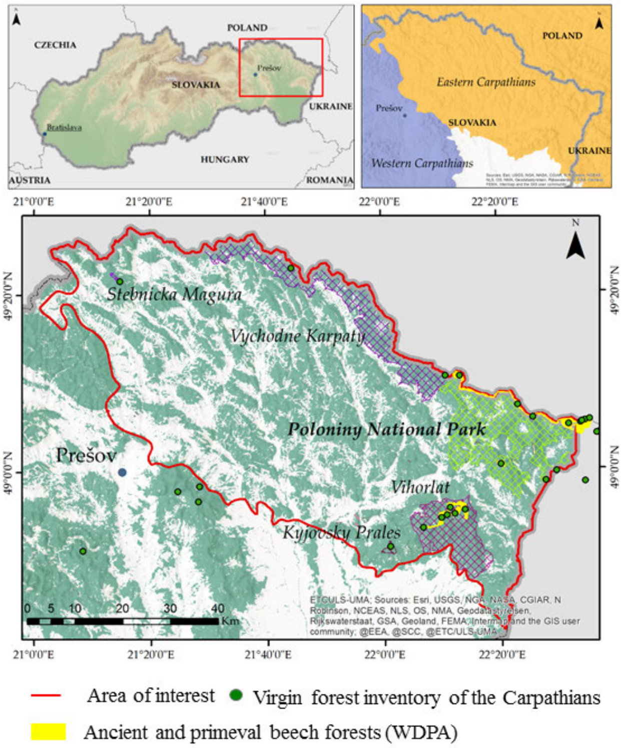

FIGURE 1. Location of the study area and the distribution of primeval beech forests within the protected areas according to the World Database on Protected Areas (WDPA).

The approach for forest disturbance risk assessment based on the time series of multisource and multiscale EO data is described by the Fig. 2 flowchart.

All processing operations are subdivided into four groups: *physiogeographic analysis* to determine the processing parameters for a particular study area; *statistical analysis* for quantitative calibration of radar data processing; *direct processing* of radar data; and, finally, *risk mapping*.

Processing begins with exploring descriptive, cartographic, regulatory, and other materials available for the study area. The investigations focused on the phenology of the dominated tree species facilitate the determination of the time interval for EO data collection. For eliminating the seasonal impact on the structural changes in the canopies, the data should be collected at the peak of vegetation when more than 90% of leaves have final shape and size but do not start to

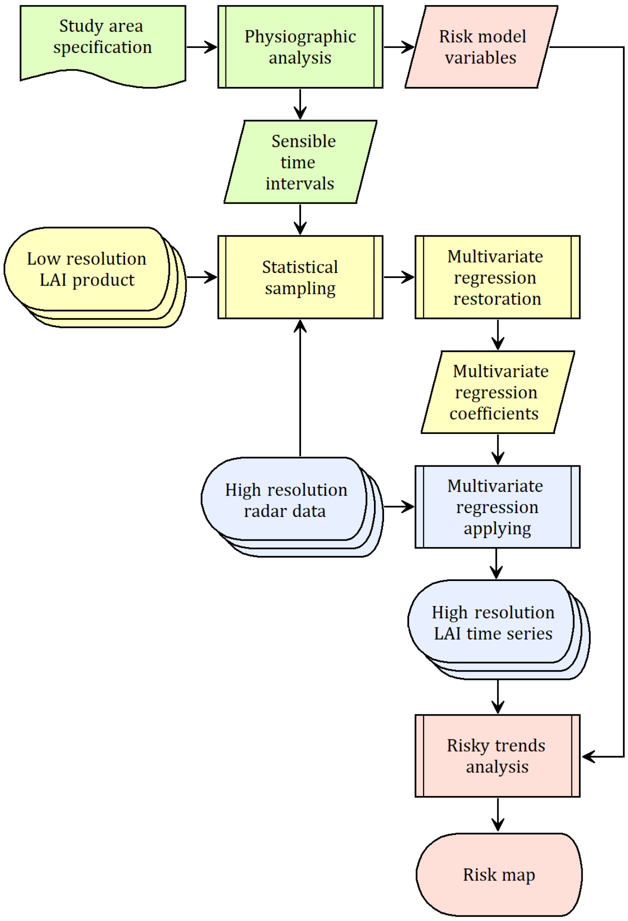

FIGURE 2. **The conceptual approach for assessing and mapping risks of forest disturbances using low-resolution LAI and high-resolution radar data.**

change their color. During this phenological phase, as a rule, LAI values reach their maximum and remain consistently high. It is important to note that, in mountain areas, phenological phases start with a delay due to gaining altitude. Therefore, we chose the DOY (day of the year) in the middle of the mentioned phase to specify the interval. A week before and a week after this DOY constitutes the interval during that EO data should be collected. As a result, time intervals for obtaining data are determined, and the risk model is formalized. The stability of the time interval of image acquisition contributes to obtaining LAI values, which depend only on external (environmental or human-induced) impact but do not depend on the current phenological phase.

Next, the co-registration of high-resolution radar data and low-resolution reference LAI data is performed. The novelty consists of unique task-orientated geostatistical sampling to stack the different-scale images described in section B into a joint high-resolution grid. This know-how involves re-projecting a low-resolution pixel grid into a higher resolution image and averaging one's pixel values within a regular spatial pattern of each low-resolution cell selected for training sample construction.

After catching statistical samples, we determine derived multivariate regression coefficients. Previously, in [32], simple non-linear regression was used. In this study, additional multiple regressors are engaged to increase the model's reliability and accuracy. Additional drivers, such as dual-polarization backscattering coefficients and local incidence angle, described in more detail in section C, were considered. Another tricky hack – the non-linear transformations of input variables, was applied to compensate for the strong nonlinearity of the intact model; in other words, multivariate regression was pre-linearized.

The restored multivariate regression is applied to multi-temporal radar data for the entire study area, resulting in a time series of high-resolution LAI maps. The formed time series allows extracting the spatial distribution of risk trends and thereby obtaining the final risk map.

Thus, the proposed approach contains the following elements of novelty: a particular technique for multiresolution imagery handling; improved multivariate regression model with heuristic pre-linearization of predictors for LAI restoration by dual polarisation radar data; risk mapping, adapted to the pixel-wise trends extraction of LAI, as an indicator of the forest vegetation condition.

B. HIGH-RESOLUTION LAI ESTIMATION

The leaf area index (LAI) was chosen as a crucial indicator to quantify the vegetation condition within the study area.

Now several long-term global LAI data products are known, including European ones [26]. The primary limitation of such products is insufficient spatial resolution. This limitation is quite substantial in vegetation mapping inside some small areas as the natural reserves of Slovakia. Another essential requirement for input data products in risk assessment with a time series is good seasonal repeatability, obtaining data at strictly defined time intervals. Optical remote sensing data products, due to the almost always present cloudiness, do not satisfy such requirements, as a rule. Therefore, we chose the Sentinel-1 remote sensing radar system for the LAI mapping within the study area, which provides the necessary spatial resolution and the repeatability of imaging [44].

There are plenty of models known for the LAI estimation by synthetic radar imaging: physically determined, semi-empirical and statistical [45], [46]. For our task, a regression approach was used. The backscattering coefficients in both polarizations – σ^0_{VV} and σ^0_{VH}, the relative difference polarization index (RDPI) r_τ [32], and the local incidence angle θ_l, taking into account the terrain geometry, were determined as regressors. The reference data for multivariate regression restoration were extracted from the 30-days composite PROBA-V LAI V1 product at 300 m resolution [27].

The complex non-linear behavior of the LAI (σ^0_{VV}, σ^0_{VH}, r_τ, θ_l) dependence forces to perform a regression analysis in two stages: first, the non-linear transformation of the original regressors, and second – the restoration of multivariate linear regression [47].

The following non-linear transformations of input regressors have been applied:

$$\frac{1}{\mathrm{th}\,(\sigma^0_{VV}+1)},\quad \frac{1}{\mathrm{th}\,(\sigma^0_{VH}+1)},\quad \frac{1}{\ln^3(r_\tau^2+1)},\quad \sin^3\theta_l \tag{1}$$

As a result, the coefficient of determination $R^2 = 0.68$ and root mean square error (RMSE) $= 0.7139$ were achieved. This accuracy of multivariate regression seems quite acceptable for practice since the basic PROBA-V LAI product RMSE ranges from 0.52 [48] up to 1.21 [49].

C. RISK ANALYSIS

Risk assessment is essential for forest disturbance trends analysis [34]–[38]. According to a study [50], [51], the concept of risk differs depending on the application area. It should be defined as a set of triplets, which are the sequence of undesirable events leading to damage, the associated probability, and the consequence. In general, risk conception is considered as a measure of an existing or a potential source of damage or hazard. Thus, the concept of risk includes the uncertainty of the occurrence of hazard [50]. In [50], risk R is defined as:

$$R = x \cdot p, \tag{2}$$

where x and p denote a given hazard or its frequency and the probability of receiving such hazard or other hazard evaluation, for example, frequency.

When considering complex systems must be accounted for the fact that typically more than one undesirable event exists, and all hazards must be considered integrally. From the point of view of risk assessment, a forest landscape can be interpreted as a complex system with many hazard factors. One possible way to indicate the damage to the forest landscape is the evaluation of LAI, an indicator of canopy structure and density, which changes (reduction) in time is considered as a risk in terms of the theoretical background of risk assessment. The LAI can be evaluated based on images from the low-resolution LAI and high-resolution radar data. The data in the form of images are analyzed and evaluated by pixels of images. Therefore, the proposed method for the risk of forest disturbance is developed to analyze image pixels in which the LAI is evaluated.

According to the definition of risk (2), forest disturbance is interpreted as a hazard, and the LAI can evaluate the hazard in a time series of multisource and multiscale EO data. The risk of forest landscape degradation is evaluated by the measure (p in (2)) discovered by the LAI changes. Therefore, this measure is calculated for pixel s because we implement an analysis by the EO data. Let us suppose that the LAI in pixel s in time i is indicated and denoted as Q_{si}. The measure of the LAI change, in this case, is computed as:

$$h_{si} = (Q_{si} - Q_{s(i-1)})/(Q_{\max}\,\Delta t) \tag{3}$$

and

$$h_{si} = (Q_{si} - Q_{s(i-1)})/(Q_{aver}\,\Delta t), \tag{4}$$

where $Q_{\max}$ and Q_{aver} are maximal and average LAI in time interval Δt.

The measures (3) and (4) in risk assessment are known as the hazard function [51]. The forest disturbance is evaluated depending on the hazard function value. Two specific coefficients are computed based on the hazard function and calculated as:

$$K = \sum_{i=1}^{T} h_{si} \tag{5}$$

and

$$K_T = h_{sT} - h_{s(T-1)}. \tag{6}$$

The first of these coefficients allows evaluating the behavior of the LAI hazard: the higher the value of this coefficient, the lower the hazard of the forest disturbance. The coefficient K is applied to evaluate the hazard in a time interval from 1 to T, where T is interpreted as the last evaluated time. The second coefficient K_T discovered the hazard in the last period only.

The problem of forest disturbance and preparation of risk maps caused the same definition gradations of risk, which can be visualized in the map. Therefore, the risk evaluation is introduced in the form of four risk gradations that are computed depending on the values of coefficients K and K_T:

- R_3 is the high risk of the degradation if $K < 0$ and $K_T < K_{T-1}$:
$$\sum_{i=1}^{T} h_{si} < 0 \text{ and } (h_{sT} - h_{s(T-1)}) < (h_{s(T-1)} - h_{s(T-2)});$$
- R_2 is the existential risk of the degradation if $K < 0$ and $K_T \geq K_{T-1}$:
$$\sum_{i=1}^{T} h_{si} < 0 \text{ and } (h_{sT} - h_{s(T-1)}) \geq (h_{s(T-1)} - h_{s(T-2)});$$
- R_1 is the potential risk of the degradation if $K \geq 0$ and $K_T < K_{T-1}$:
$$\sum_{i=1}^{T} h_{si} \geq 0 \text{ and } (h_{sT} - h_{s(T-1)}) < (h_{s(T-1)} - h_{s(T-2)});$$
- R_0 is no risk of the degradation if $K \geq 0$ and $K_T \geq K_{T-1}$:
$$\sum_{i=1}^{T} h_{si} \geq 0 \text{ and } (h_{sT} - h_{s(T-1)}) \geq (h_{s(T-1)} - h_{s(T-2)}).$$

Based on the equations described above, the R_3 risk decreases LAI over the entire study and the last time interval. The R_2 risk indicates a damaging increase in LAI over the entire study interval but positive over the last two years. The R_1 risk marks a positive trend in LAI over the entire study interval but indicates degradation in recent years. The R_0 risk indicates a trend of increasing LAI both for the whole time and for the last couple of years.

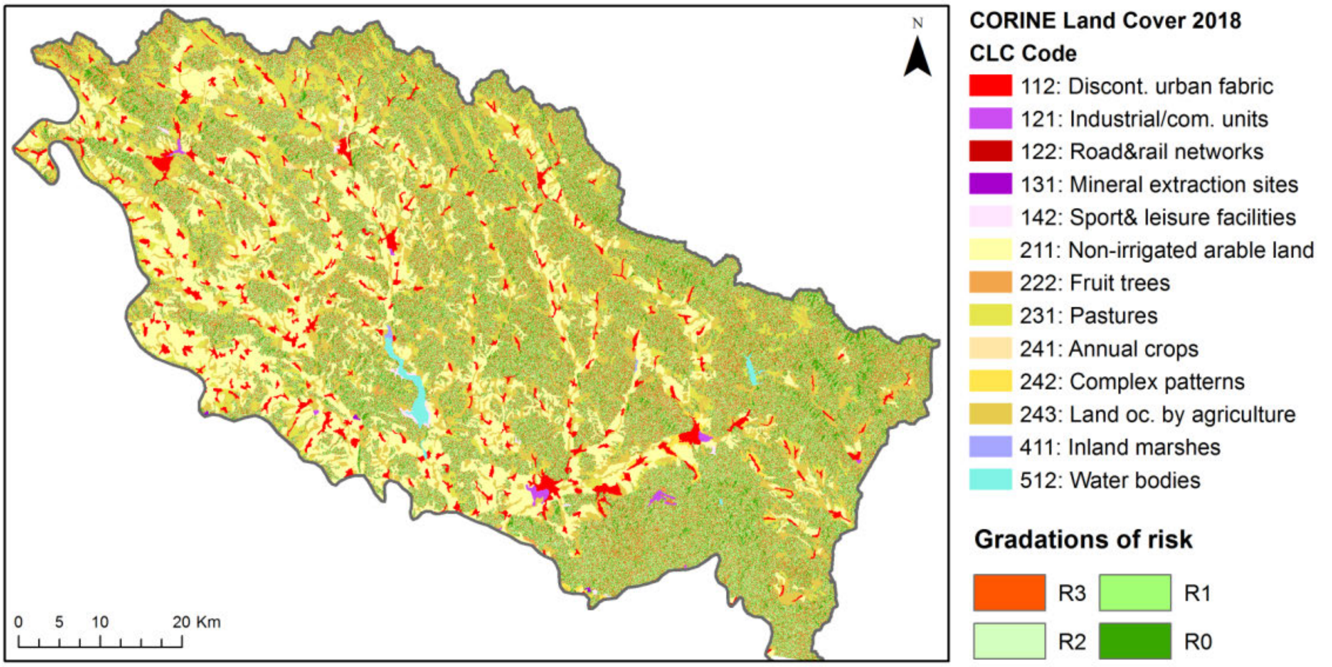

FIGURE 3. The map of forest disturbance risk within the study area. The forest cover is delineated using the CLC2018 dataset. The risk of forest disturbance is referred to four gradations: R_3 is the high risk, R_2 is the existential risk, R_1 is the potential risk, and R_0 is no risk.

IV. RESULTS

A. EARTH OBSERVATION DATA

After mandatory registration, Copernicus Open Access Center (previously known as Sentinels Scientific Data Hub) provides full and free access to all Sentinel-1, Sentinel-2, and Sentinel-3 satellite products. The resource has a cartographic web interface and a developed search system, choosing, ordering, and receiving Copernicus information products (https://scihub.copernicus.eu/dhus/).

The data were collected for the two-week interval with the 165 DOY in the middle. It was specified considering the European beech phenology dominated in the Slovak Eastern Carpathians [52], [53].

Sentinel-1 ground range detected (GRD) Level-1 processing products were used to perform the study, which are focused radar images with coherent accumulation and projection procedures to the earth's surface using the Ellipsoid model.

LAI 300 m Version 1 product by PROBA-V satellite system was downloaded from the Copernicus Global Land Service that provides bio-geophysical products of the global land surface. These products are almost 9-month temporal composition adapted to ensure an approximate (10-day) estimate and consistent estimates in real-time until the consolidated value is reached (Table 1).

TABLE 1. List of used remote data and their characteristics.

Radar data	LAI remote data
Sentinel-1A, IW, GRDH, 13/06/2015	PROBA-V1.0, LAI300, 22/11/2014-10/08/2015*
Sentinel-1A, IW, GRDH, 07/06/2016	PROBA-V1.0, LAI300, 23/11/2015-10/08/2016*
Sentinel-1A, IW, GRDH, 14/06/2017	PROBA-V1.0, LAI300, 22/11/2016-10/08/2017*
Sentinel-1A, IW, GRDH, 09/06/2018	PROBA-V1.0, LAI300, 22/11/2017-10/08/2018*
Sentinel-1A, IW, GRDH, 16/06/2019	PROBA-V1.0, LAI300, 22/11/2018-10/08/2019*
Sentinel-1A, IW, GRDH, 10/06/2020	PROBA-V1.0, LAI300, 23/11/2019-10/08/2020*
Sentinel-1A, IW, GRDH, 17/06/2021	Sentinel-3/OLCI, LAI300-RT6, 20/06/2021

* representative date – 20/06 in each study year.

B. HIGH-RESOLUTION LAI TIME SERIES

Using the processed radar images (Table 1) and regression (1), according to the data flow in Fig. 2, a time series was obtained, consisting of seven spatial distributions of LAI in the study area. The spatial resolution of the LAI maps is similar to the resolution of the used Sentinel-1 imagery and equal to 10 m. These high-resolution LAI temporal maps formed the input data set for further risk analysis.

C. RISK MAP

The proposed approach for forest disturbance risk assessment based on the time series of multisource and multiscale EO data has been used to develop map of forest disturbance risk of Slovak Eastern Carpathians (see section II). The developed map of forest disturbance risk is shown in Fig. 3. Fig. 4 shows the distribution of forest disturbance

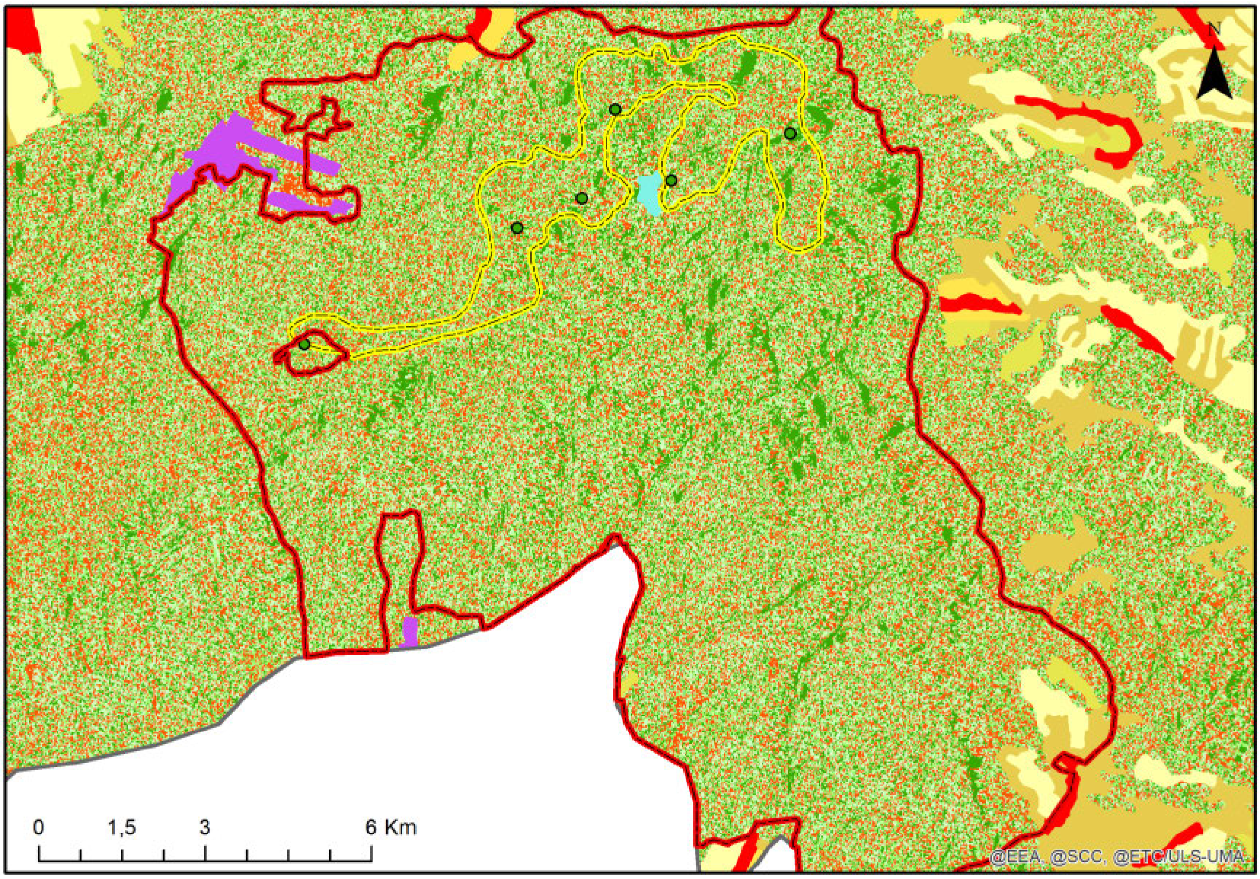

FIGURE 4. The fragment of the resultant map for the Vihorlat Protected Landscape Area includes the World Heritage site with primeval beech forests.

risk within the Vihorlat Protected Landscape Area, including the World Heritage site with primeval beech forests. These maps have been developed by using the CORINE Land Cover dataset updated for 2018 (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018). The CORINE Land Cover dataset consists of an inventory of land cover in 44 classes. The maps in Fig.3 and Fig.4 have some of them which are indicated in the legend. Among them, the forest-related classes are marked by four additional colors depending on the risk of disturbance.

The maps in Fig.3 and Fig.4 have one legend and each pixel of these maps for forest presents one of the four gradations of risk of the forest disturbance assessed from the trend of LAI changes revealing the reduction or recovery of the forest structure and density. The spatial resolution of the obtained map enables one to investigate in detail the distribution of forest disturbance risk within different forest conservation sites, from sizable protected landscape areas to small, even point sites with primeval forests.

V. DISCUSSION

Therefore, the proposed approach enables assessing forest disturbance risk based on the time series of LAI PROBA-V LAI V1 product at 300 m resolution and Sentinel-1 C-band SAR GRD product at 10 m resolution. Moreover, considering the capacity of radar surveying, it is possible to provide such an assessment for the mountain forests.

The obtained results reveal three main advantages of the proposed approach. The first one is the spatial resolution of the final map that makes it possible to detail the distribution of the assessed risk of forest disturbance for protected areas different in size, even the smallest one. The approach to LAI estimation suggested in the approach provides a ten-fold refinement of resultant LAI maps compared to the original PROBA-V LAI V1 product. Thus, the obtained results also demonstrate a good potential of a joint using well-verified LAI products of low spatial resolution and radar satellite imagery of high resolution to estimate forest LAI in the rugged terrain of mountains.

The second one is to ensure the continuity of LAI measurements, which are obtained at strictly defined time intervals. That ensures the data completeness for identifying forest structure LAI-based changes and significantly affects the accuracy of the subsequent risk assessment. Like the first one, this advantage rises from the use of Sentinel-1 SAR data.

The third one is the significant minimization of LAI ground measurements. Practically, there is no direct need for such measurements for the suggested approach to LAI estimation

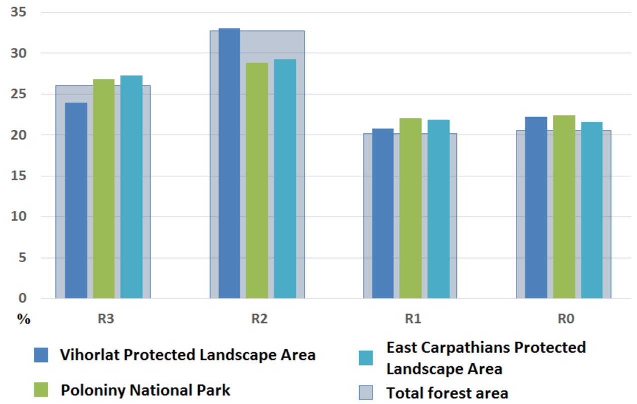

FIGURE 5. According to the CORINE classification, the percentage distribution of forest disturbance risks across reserves to their area and throughout the study area includes forests.

due to using the PROBA-V LAI V1 product with good precision [21]. Nevertheless, it should be emphasized that LAI ground measurements, forest ground observation, and inventory data are critical for validating the proposed approach and further interpreting the obtained results.

The main achievement of the proposed approach refers to the definition of the four gradations of evaluated risk depending on the observed changes of forest structure both over the entire study time interval and over the last time interval. Two transitional gradations between the high absolute risk and almost total absence of risk contribute to a comprehensive view of forest disturbance processes.

The results of applying the proposed approach give the answers to the questions posed at the beginning. Thus, after conducting the study, we analyzed the main results collected from the risk map, such as the percentage distribution of forest disturbance risks throughout the study area as well as distribution throughout the biggest reserved territories: Poloniny National Park, Vihorlat, and East Carpathians Protected Landscape Areas (Fig.5).

There is no substantial difference in the rate of forest disturbance risk across the primeval and managed forests. Although, risk absence (R_0) and positive trend over the entire study interval (R_1) are predictably higher in the protected areas. The predominance of the existential risk (R2), especially in managed forests, indicates a negative trend for forest disturbance over the entire study interval, but positive over the last two years, probably, may be attributed to a decrease in logging intensity in these recent years. Experts connect forest disturbance's high risk (R3) in protected areas with unsustainable logging [7].

VI. CONCLUSION

Thus, the proposed approach for risk assessment of forest disturbance based on time series of multisource and multiscale EO data has demonstrated promising results. It can be recommended to analytics and decision-makers in forest management and conservation.

The proposed approach also can be extended to other regions of mountain forests in Slovakia. It also can be recommended for implementation in other countries where the primeval forests have remained (https://whc.unesco.org/en/list/1133/). Slightly modified, it also can be applied to risk the assessment of forest disturbance of the lowlands.

It is worth directing future research at the involvement of data on forest ground observation to validate the proposed approach and proper interpretation of the obtained results. Also, the primary regression model used for LAI determining needs to be elaborated and expanded to provide a more correct and reliable tracing of all factors affecting radar backscattering. Moreover, further implementing the proposed approach as a web service [54] is highly advisable.

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