Monitoring post-fire forest regrowth using Differenced Disturbance Index classification

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ABSTRACT

Forest fires are natural ecosystem processes with significant environmental impact. Monitoring the recovery processes is vital to ecological research. The aim of this study is monitoring post-fire forest regrowth using remote aerospace methods and data. To achieve this goal, Differenced Disturbance Index classification was applied for quantitative assessment of the post-fire forest regrowth. The study area is situated in the northeastern part of Rhodope Mountains, near Chernyovtsi village, 15 km from the city of Kardzhali, Bulgaria. A fire took place on October 1, 2012 and affected an area of 15 ha with mixed forests and coniferous forests. For the post-fire forest regrowth monitoring Landsat (ETM+, OLI and OLI-2) satellite imageries were used once per year in August for the 10-year study period – 2012-2022. After applying the proposed methodology, the results are classified maps exhibiting the post-fire regrowth.

The data and results of this research will be able to serve Destination Earth (DestinE), which is an ambitious initiative of the European Union to create a digital model of the Earth that will be used for monitoring the effects of natural and human activities on our planet, prediction of extreme events and adapting policies to the climate challenges. The data and models will serve the Bulgarian initiative for the construction of the Digital Twins, which is being pilot developed in the department of Aerospace Information, Space Research and Technology Institute – Bulgarian Academy of Sciences. Open Data were used in this study, with the aim of promoting the Open science policy and FAIR principles as much as possible.

Keywords: Remote Sensing, Post-fire forest regrowth, Disturbance Index, Landsat, Bulgaria

1. INTRODUCTION

Wildfires are natural ecosystem processes that considerably disturb the functioning of ecosystems. Monitoring post-fire forest regrowth is crucial for receiving knowledge to help forest ecosystem recovery after fires. Remote aerospace methods and data provide effective tool in agriculture[1-3] as well as in forestry – forecasting, monitoring, mapping and restoration of burnt areas. Aerospace remote sensing methods are a high-tech tool for reliable and large-scale monitoring of recovery processes occurring in forest ecosystems after fire[4-7].

Spectral indices and reflectance values are mainly used for vegetation processes following disturbances after fire[8-10]. Spectral indices generally rely on greenness measurements of red – near-infrared vegetation indices on the basis of different algebraic combinations between original spectral bands[11]. Vegetation indices help the study of forest ecosystems disturbance, but they are not accurate enough to study the regrowth processes in forest ecosystems observed after a fire. The differences in fire damage, caused by differences in undergrowth, species diversity, and the different regenerative abilities of forest with different tree species are the main reason for this.

Disturbance Index (DI)[12] was examined to be a relatively efficient approach to detect the forest disturbance and monitor its change. The higher accuracy of the index in comparison to standard vegetation indices is based on the linear orthogonal transformation of multispectral satellite images – Tasseled Cap Transformation (TCT)[13-15] which increases the degree of identification of the three main components changing during fire – soil, vegetation and moisture[16]. Different sensors use various transformation matrices fixed only to them. For monitoring post-fire regrowth dynamics in this study we used transformation matrices fixed for Landsat sensors[17,18].

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DI highlights the unvegetated spectral signatures associated with stand-replacing disturbance and separates them from all other forest signatures. When viewed sequentially, the time series of DI images provide a direct way to highlight pixels that changed from an average to a disturbed forest condition[12].

The Landsat data is widely used in forest monitoring[19-23], but their applicability for detailed vegetation studies is limited, especially by their spatial and spectral resolution[24]. However, Landsat program offers a chance to study the long-term dynamics of forest ecosystems via long-term data series.

2. STUDY AREA

Monitoring post-fire forest regrowth was performed on the territory of a burnt area near Chernyovtsi village, Bulgaria. The selection of the study area was based on several criteria: the burnt area should be large enough (> 5 ha) to allow mapping with Landsat data, the fire event should be before 2016 so there is enough time for regrowth processes to start, the presence of aerial images for visual interpretation and validation. Thus taking into account the above mentioned criteria and limitations the selected test fire is located next to Chernyovtsi village.

The Chernyovtsi test fire (450 - 510 m above sea level) is situated in the northeastern part of Rhodope Mountains, near Chernyovtsi village, 15 km from the city of Kardzhali, Bulgaria (Figure 1).

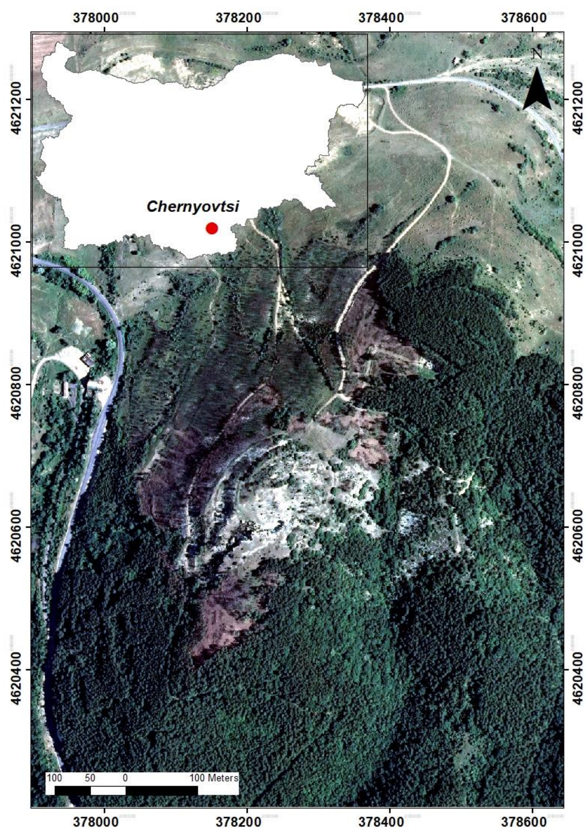


Figure 1. Location of the study area – Chernyovtsi, Bulgaria. Coordinates: 41°43’40’’N; 25°32’07’’E. The red point in the small map shows the location of the area shown on the main image. Background image source: Aerial image, 2013.

A fire took place on October 1, 2012 and affected an area of 15 ha with mixed forests and coniferous forests. Mixed forests consist of Turkey oak (*Quercus cerris L.*), Hungarian oak (*Quercus frainetto T e n*) and Oriental hornbeam

(*Carpinus orientalis M i l l.*) with Mediterranean elements in places with secondary origin. The native deciduous forests in the region refer to the Thracian province of the European deciduous forest area. However, because of the erosion processes in the 1950s and the expansion of bare lands, a massive afforestation with coniferous forests – Black pine (*Pinus nigra Arn.*), has been performed.

The area is characterized by Continental-Mediterranean climate. The soils are Chromic Cambisols. The forest ecosystems in this part of Bulgaria have been under stress in the summers during the last years due to frequent and prolonged droughts related to climate change[25,26]. The topography influenced the development of the wildfire as well. However, the forest ecosystems were not entirely damaged, since the fire occurred during the winter. The cold and humid conditions during the winter, the higher moisture content in the forest ecosystems determined the lower intensity of the fire, which affected the forest ecosystems less.

3. METHODS AND DATA

3.1. Data acquisition

Monitoring the degree of disturbance and post-fire regrowth processes was performed on the territory of the test area for the study period – 2012-2022. The imagery acquisition was carried out taking into account the vegetation period of the forest ecosystems and the absence of clouds and cloud shadows over the study area. Landsat (ETM+, OLI and OLI-2) satellite imageries were used once per year in August. The satellite images from Landsat are freely available through the US Geological Survey's online platform – Earth Explorer (https://earthexplorer.usgs.gov/)[27]. The dates of the satellite images used for the purpose of the post-fire regrowth monitoring and the sensor of which they were obtained are shown in Table 1.

Table 1: Image acquisition dates

Date of acquisition	Sensor
03/09/2012	Landsat ETM+
13/08/2013	Landsat OLI
16/08/2014	Landsat OLI
26/08/2015	Landsat OLI
21/08/2016	Landsat OLI
24/08/2017	Landsat OLI
18/08/2018	Landsat OLI
21/08/2019	Landsat OLI
23/08/2020	Landsat OLI
03/08/2021	Landsat OLI
30/08/2022	Landsat OLI 2

Aerial images[28] with very high resolution (VHR) from 2013 (one year after the fire) were used for visual interpretation and test area selection as well as validation. Their spatial resolution is ≤ 0.4 m.

The proposed approach using Differenced DI classification for post-fire regrowth monitoring was validated in a previous study with the help of a method involving the delineation of dynamic boundaries for spatial accuracy assessment. That previous study used VHR satellite data, including World View (2/3) and GeoEye (1) sensors for validation[29].

3.2. Multispectral Image Processing

The Differenced DI calculated for vegetation regrowth dynamics are considered as classified raster thematic maps. The data processing of multispectral satellite images included basic operations such as georeferencing, subsetting, stacking multiband images, tasseled cap transformation, generating spectral indices – DI, dDI (described in Table 2).

Generation of DI was based on TCT, applied on stacked multi-band images. After applying TCT, the results were multi-band images containing three layers – Wetness (TCW), Brightness (TCB), and Greenness (TCG). Normalization steps followed in order to normalize the radiometric change. Afterwards TCB, TCG and TCW were combined linearly to acquire DI[14]. The classified output rasters have a spatial resolution of 30 m.

Table 2. Spectral indices used for classified raster thematic maps.

Spectral index	Abriviation	Formula	References
Disturbance Index	DI	nTCB – (TCG + nTCW)	Healey et al., 2005[12]
Differenced Disturbance Index	dDI	$DI_{post\text{-}fire} - DI_{pre\text{-}fire}$	Mazek et al., 2008[22]

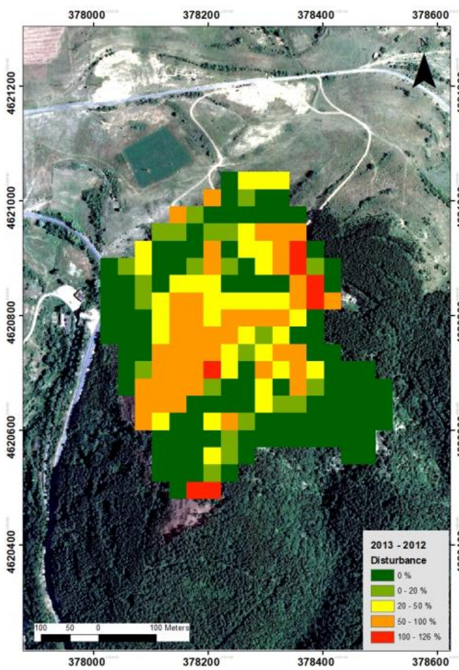
4. RESULTS AND DISCUSSIONS

For the purpose of post-fire regrowth monitoring dDI rasters were generated on a yearly basis, indicating the areas and intensity of forest disturbance and regrowth after fire, actual at that certain year. The thematic raster classified by the intensity of recovery are compared with the values one month before the fire (2012), in quantitative values (%).

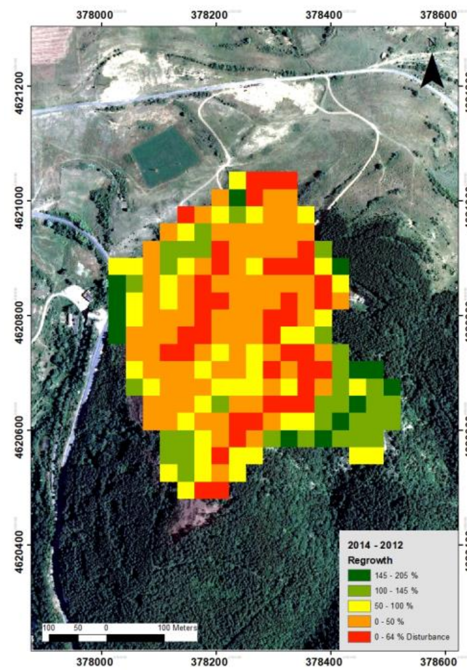
The concept of DI assumes that high TCB and low TCG and TCW values are typical for disturbed stands and DI values are high positive, while undisturbed or fully recovered stands exhibit low TCB and high TCG and TCW values resulting in low negative DI values[15].

Figure 2 shows the dDI classified thematic raster for the study period – 2012-2022 on the territory of the burnt forest area. Figure 2 A) shows the post-fire disturbance map one year after the fire (2013). Two Landsat images were used – 09/03/2012 (Landsat ETM+) and 13/08/2013 (Landsat OLI) for representing the disturbance one year after the fire. The dark green color depicts areas with 0% disturbance – actually the unburnt forests. The light green color shows slightly affected forests – 0-20 %, the yellow color – forests with 20-50 % disturbance, the orange color – forests with 50-100 % disturbance and the red color – forests with 100-126 % disturbance.

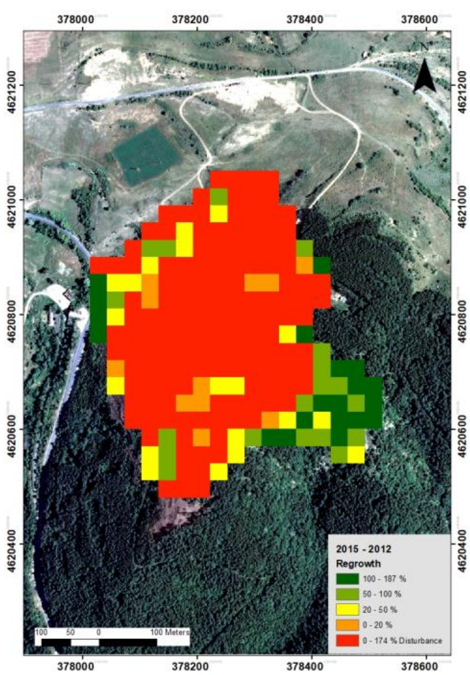
Figure 2 B) – G) show the post-fire regrowth maps representing the disturbance and regrowth for the post-fire monitoring (2 – 10 years after the fire) compared with the values from one year before the fire, in percentages. The green, yellow and orange colors depict regrowth, while the red colors indicate for disturbance. The percentages are shown in the legends (Fig. 2).


378000
378200
378400
378600
4621200
4621000
4620800
4620600
4620400
2013 - 2012
Disturbance
0 %
0 - 20 %
20 - 50 %
50 - 100 %
100 - 126 %
100 50 0 100 Meters

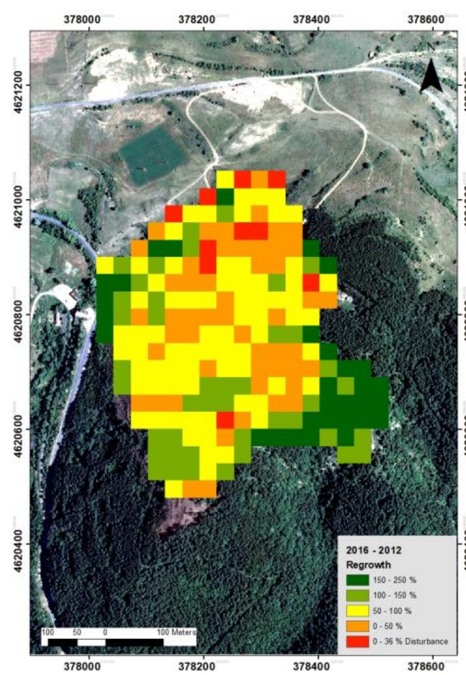
A)


378000
378200
378400
378600
4621200
4621000
4620800
4620600
4620400
2014 - 2012
Regrowth
145 - 205 %
100 - 145 %
50 - 100 %
0 - 50 %
0 - 64 % Disturbance
100 50 0 100 Meters

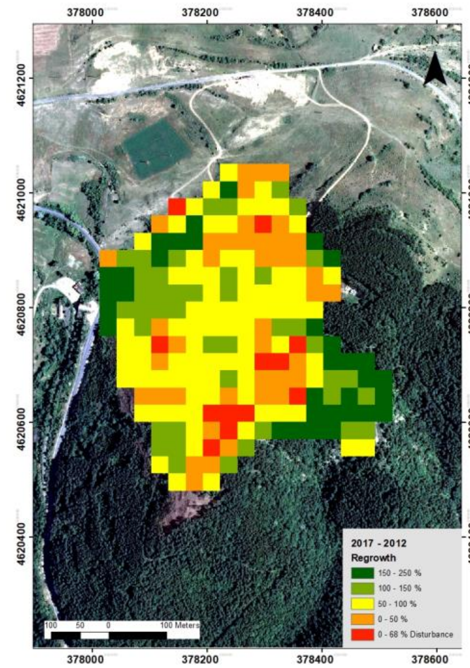
B)


378000
378200
378400
378600
4621200
4621000
4620800
4620600
4620400
2015 - 2012
Regrowth
100 - 187 %
50 - 100 %
20 - 50 %
0 - 20 %
0 - 174 % Disturbance
100 50 0 100 Meters

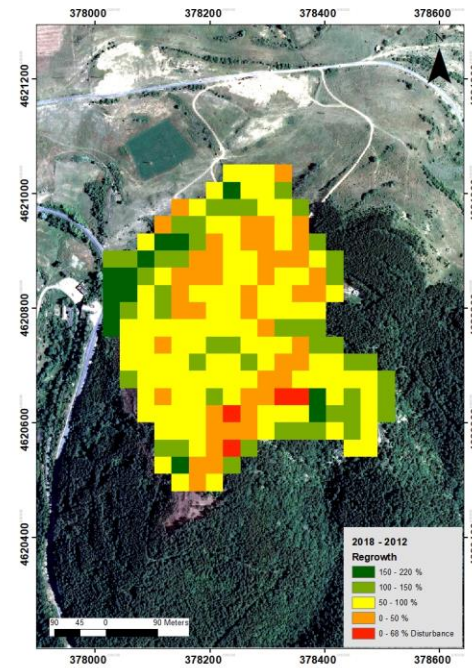
C)


378000
378200
378400
378600
4621200
4621000
4620800
4620600
4620400
2016 - 2012
Regrowth
150 - 250 %
100 - 150 %
50 - 100 %
0 - 50 %
0 - 36 % Disturbance
100 50 0 100 Meters

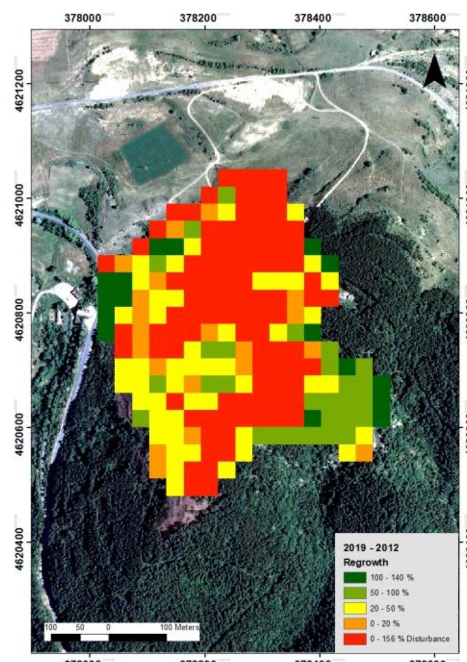
D)


2017 - 2012
Regrowth
150 - 250 %
100 - 150 %
50 - 100 %
0 - 50 %
0 - 68 % Disturbance
100 50 0 100 Meters

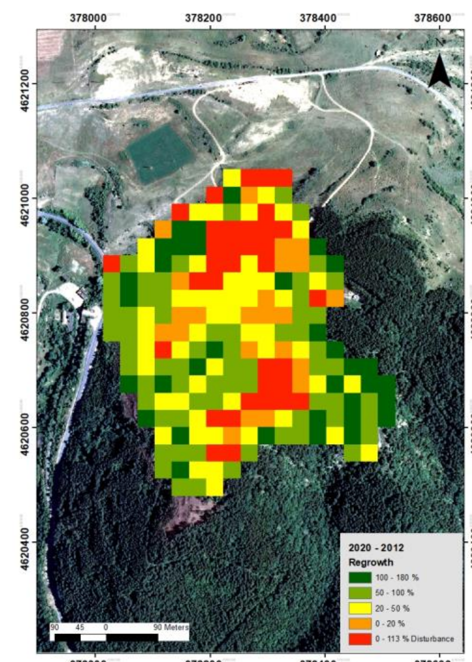
E)


2018 - 2012
Regrowth
150 - 220 %
100 - 150 %
50 - 100 %
0 - 50 %
0 - 68 % Disturbance
90 45 0 90 Meters

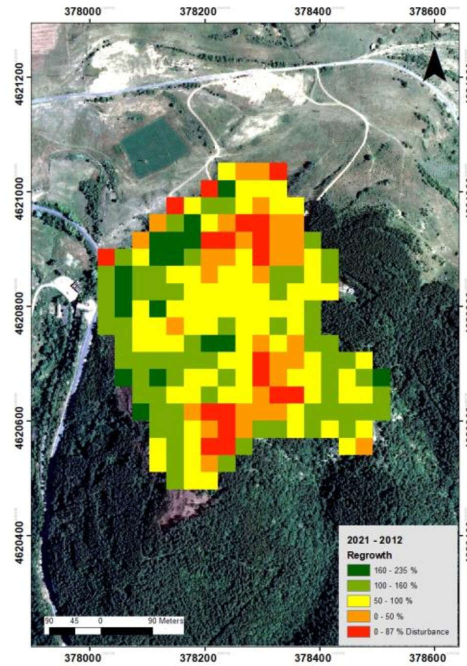
F)


2019 - 2012
Regrowth
100 - 140 %
50 - 100 %
20 - 50 %
0 - 20 %
0 - 156 % Disturbance
100 50 0 100 Meters

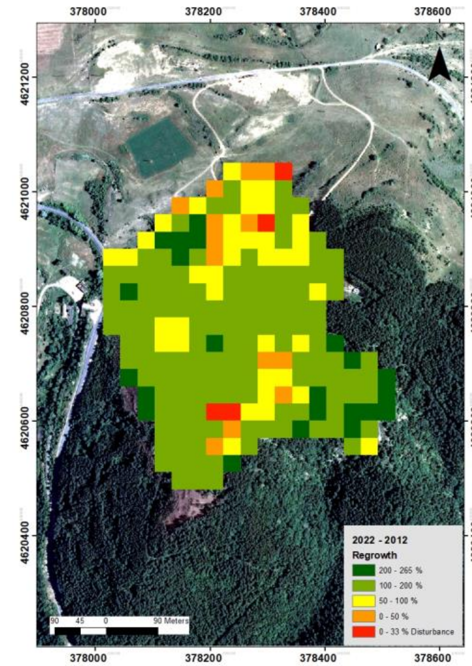
G)


2020 - 2012
Regrowth
100 - 180 %
50 - 100 %
20 - 50 %
0 - 20 %
0 - 113 % Disturbance
90 45 0 90 Meters

H)



I)



J)

Figure 2. A) Post-fire disturbance map one year after the fire (2013) (%), Post-fire regrowth maps for B) 2014, C) 2015, D) 2016, E) 2017, F) 2018, G) 2019, H) 2020, I) 2021, G) 2022 (%).

After visual interpretation of the results obtained for post-fire disturbance and regrowth maps, some main conclusions are summarized as follows:

- The burnt area can be reliable detected using dDI rasters (Figure 2 A)).

- Burn severity (the intensity of forest disturbances) after fire can be appreciated using the dDI classified thematic raster (Figure 2 A)).

- dDI classified thematic maps showed a good performance in monitoring post-fire disturbances – in more forested areas.

- dDI classified thematic maps can be used for post-fire regrowth assessment (Figure 2 B) – J)). However, using the proposed approach it can not be recognized if the regrowth is due to forest recovery or other types of vegetation (herbaceous and shrubby vegetation, etc.)

- dDI classified thematic maps exhibit different quantitative values of disturbance/recovery – according to the different climate conditions that influence the recovery, the following year may exhibit lower recovery rates than the previous one (Figure 2 B), C)). For that reason, for the purpose of post-fire monitoring using the proposed approach the better option is to compare with one base year – before the fire, rather than the previous year.

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