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OBSERVATION OF SPECTRAL INDICES PERFORMANCE FOR POST-FIRE FOREST MONITORING

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Abstract

Monitoring post-fire forest disturbances and subsequent recovery is vital for the management and preservation purposes of the forest ecosystems. This study aimed to assess forests' damages and regrowth dynamics after fire using remotely sensed data and to compare its reliability for post-fire monitoring in different forest environments. This paper compared forest regrowth dynamics applying selected spectral indices – Differenced Normalized Difference Vegetation Index (dNDVI), Differenced Normalized Burn Ratio (dNBR), and Differenced Disturbance Index (dDI). The post-fire environmental impact and recovery processes were performed on the territory of the three fires in Bulgaria – Ardino, Bistrishko branishte, and Perperek.

Introduction

Due to global climate change the number of wildfires is increasing resulting in disturbances to forest ecosystems. Monitoring post-fire forest disturbances and subsequent regrowth processes is of great importance for arranging activities for forest ecosystem preservation. Aerospace remote sensing methods are a high-tech tool for reliable and large-scale monitoring of recovery processes occurring in forest ecosystems after a fire [1, 2]. Many researchers apply spectral vegetation indices (VIs) to monitor forest regrowth dynamics [3, 4]. Normalized Difference Vegetation Index (NDVI) [5] uses spectral reflectance characteristics (SRC) of vegetation in Red and Near-infrared (NIR) bands and Normalized Burn Ratio (NBR) [6] – NIR and Short-wave infrared (SWIR) bands. Disturbance Index (DI) [7] uses the linear orthogonal transformation of multispectral satellite images – Tasseled cap transformation (TCT) [8, 9], that increases the degree of identification of the main landscape components changing during a fire – soil, vegetation, and moisture/water.

The purpose of the present study was to observe forest disturbances and regrowth dynamics after a fire in three different forest environments, using dNDVI, dNBR, and dDI.

Study area

Post-fire forest disturbances and regrowth monitoring were performed on the territory of three study fires in Bulgaria: Ardino, Bistrishko branishte, and Perperek (Fig. 1). The test sites were initially described in a previous study assessing the performance of selected spectral VIs for post-fire monitoring [10].

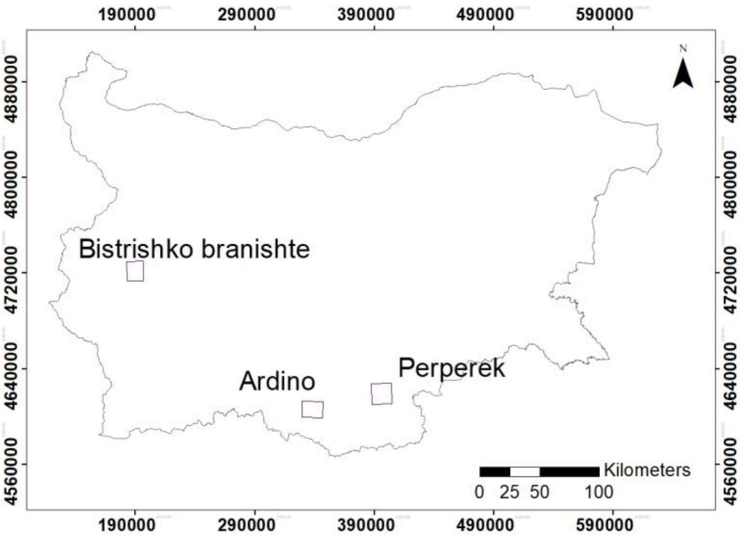


Fig. 1. Location of the study areas on the territory of Bulgaria

A fire broke out on 29 July, 2016 near Ardino town (Fig. 1), located in the southeastern part of Rhodope Mountains, Bulgaria. The fire affected 100 ha of coniferous forests. The climate in the area is Continental-Mediterranean, with mountainous elements. The slopes are mainly with east, southeast, and south exposures, which determine warm and dry conditions for vegetation regeneration. After the fire, the damaged forest stands were removed by sanitary logging in 2018.

The second fire occurred on July 1, 2012, in the nature reserve Bistrishko branishte, situated on the northeastern slope of Vitosha Mountain, next to Sofia, Bulgaria (Fig. 1). The fire affected 70 ha mostly dry and dead spruce forests because of the tornado that occurred in 2001 and bark beetle spots in 2004. Due to its preservation status as a nature reserve, no sanitary loggings were conducted in the area. The climate is mountainous, and the slopes are mostly with northwest and north exposures, determining cold and wet conditions for vegetation regrowth.

A fire occurred on November 21, 2015, in the northeastern part of the Rhodope Mountains, near Perperek village, Bulgaria (Fig. 1). The fire burned 30 ha of coniferous forests. The damaged forest stands were removed by sanitary loggings in 2017. The climate in this area is Continental-Mediterranean and the slopes have northeastern exposure. The character of the relief and gentler slopes provide more favorable conditions for vegetation development.

Data and methods

Forest disturbances were assessed, and regrowth monitoring was conducted for the study period – 2012-2021, using Landsat (ETM+ and OLI) and Sentinel 2 (A and B) satellite imageries (Table 1). Sentinel 2 images were downloaded through Copernicus Open Access Hub [11], and Landsat images – from the US Geological Survey – Earth Explorer [12].

Table 1. Satellite imageries used for the calculation of dNDVI, dNBR, and dDI

Bistrishko branishte		**Ardino**		**Perperek**	
Date	*Sensor*	*Date*	*Sensor*	*Date*	*Sensor*
29/06/2012	*Landsat ETM+*	11/07/2016	*Sentinel 2A*	07/11/2015	*Landsat OLI*
15/07/2012	*Landsat ETM+*	05/08/2016	*Sentinel 2A*	25/12/2015	*Landsat OLI*
19/08/2013	*Landsat ETM+*	15/07/2017	*Sentinel 2A*	21/08/2016	*Sentinel 2A*
05/07/2014	*Landsat ETM+*	24/08/2018	*Sentinel 2A*	15/07/2017	*Sentinel 2A*
08/07/2015	*Landsat ETM+*	29/08/2019	*Sentinel 2A*	29/08/2018	*Sentinel 2A*
13/07/2016	*Sentinel 2A*	28/08/2020	*Sentinel 2A*	24/08/2019	*Sentinel 2A*
27/08/2017	*Sentinel 2A*	23/08/2021	*Sentinel 2A*	23/08/2020	*Sentinel 2A*
01/09/2018	*Sentinel 2A*			18/08/2021	*Sentinel 2A*
12/08/2019	*Sentinel 2A*				
05/09/2020	*Sentinel 2A*				
01/08/2021	*Sentinel 2A*				

The observation of forest disturbances and post-fire regrowth monitoring were performed using selected spectral indices – dNDVI, dNBR, and dDI. Table 2 presents the indices formulas.

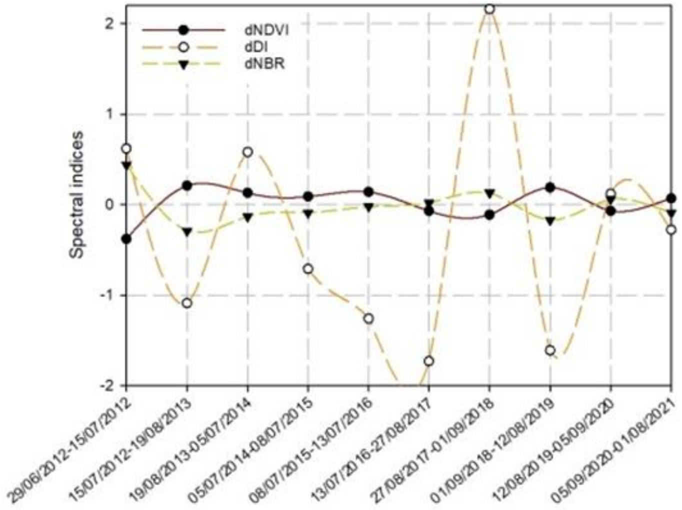
Table 2. Spectral indices used for the regrowth monitoring

Index	Abbreviation	Formula
Normalized Difference Vegetation Index	NDVI	$\frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$
Differenced Normalized Difference Vegetation Index	dNDVI	NDVI $_{\text{post-fire}}$ – NDVI $_{\text{pre-fire}}$
Normalized Burn Ratio	NBR	$\frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}$
Differenced Normalized Burn Ratio	dNBR	NBR $_{\text{pre-fire}}$ – NBR $_{\text{post-fire}}$
Disturbance Index	DI	$nBR - (nGR + nW)$
Differenced Disturbance Index	dDI	DI $_{\text{post-fire}}$ – DI $_{\text{pre-fire}}$

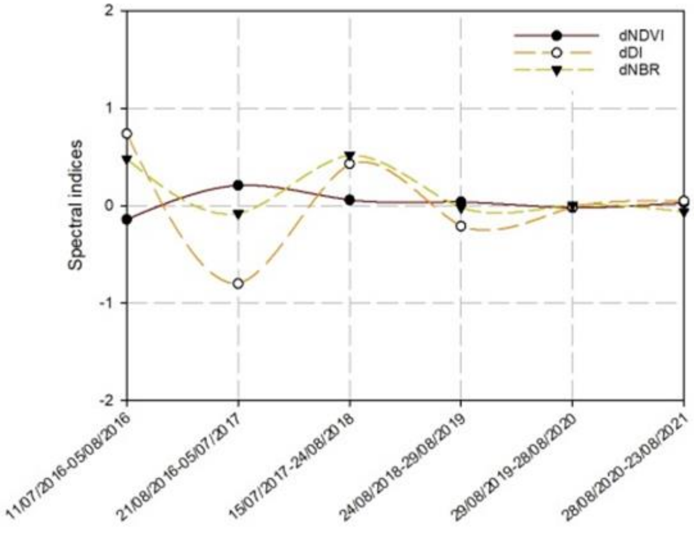
The proposed methodology using the selected spectral indices for post-fire regrowth monitoring was validated in a previous study with the help of a method involving the delineation of dynamic boundaries for spatial accuracy assessment [10]. That previous study used VHR satellite data, including World View (2/3) and GeoEye (1) sensors, for validation.

Post-fire forest monitoring

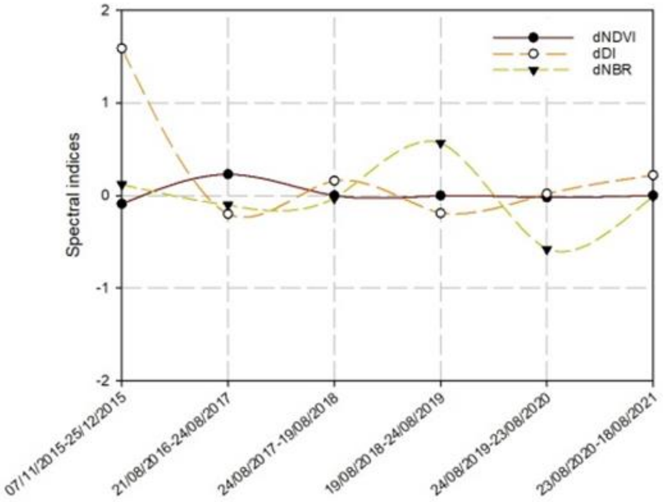
For the post-fire monitoring, dNDVI, dNBR, and dDI rasters were generated on a yearly basis and compared with the values from the previous year. Fig. 2 summarizes the mean values of differenced indices on the territory of Ardino, Bistrishko branishte, and Perperek test sites. The negative mean dNDVI and the high positive mean dDI and dNBR values for all test areas indicate high disturbances immediately after the fire, corresponding to the left-most points in each plot in Fig. 2. The high dNDVI and the low dDI and dNBR mean values for all test sites indicate high recovery rates at the beginning of the study period – one year after the fire. In the following years, the indices values show the dynamics in the forests' regrowth, indicating clearly its interruption due to sanitary logging in Ardino (2018) and Perperek (2017) (Fig. 2).


dNDVI
dDI
dNBR
Spectral indices
2
1
0
-1
-2
29/06/2012-15/07/2012
15/07/2012-19/08/2013
19/08/2013-05/07/2014
05/07/2014-08/07/2015
08/07/2015-13/07/2016
13/07/2016-27/08/2017
27/08/2017-01/09/2018
01/09/2018-12/08/2019
12/08/2019-05/09/2020
05/09/2020-01/08/2021

a)


dNDVI
dDI
dNBR
Spectral indices
2
1
0
-1
-2
11/07/2016-05/08/2016
21/08/2016-05/07/2017
15/07/2017-24/08/2018
24/08/2018-29/08/2019
29/08/2019-28/08/2020
28/08/2020-23/08/2021

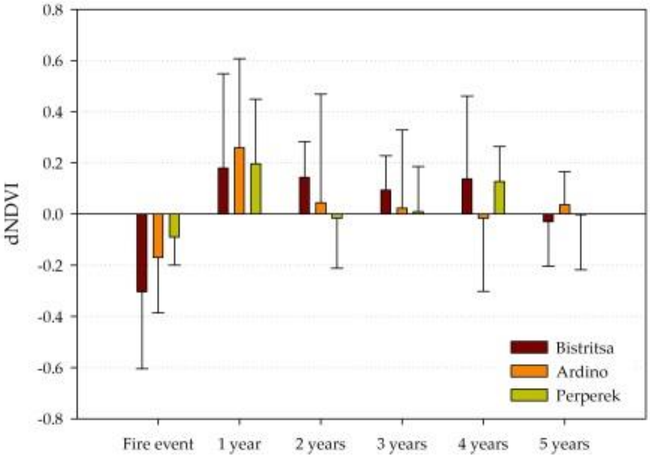
b)



c)

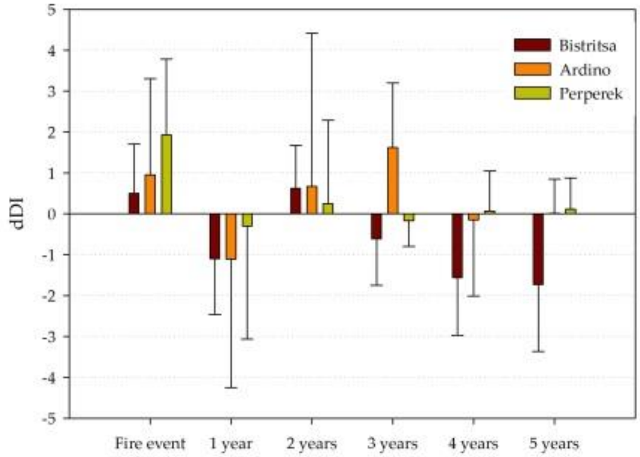
Fig. 2. dNDVI, dNBR, and dDI mean values for Bistritsa (a), Ardino (b), and Perperek (c) test sites

Fig. 3 plots the standard deviations (SD) of each of the indices, calculated based on minimum, maximum, and mean values for each test site for five years, starting from the fire event. The SD values exhibit the dynamics of the natural environment. The highest SD values are observed during the fire event years and the years of the sanitary logging carried out afterward. This dependence is particularly noticeable in the SD values of dDI and dNBR, indicating increasing spectral reflection of bare soils. Amongst the test sites, Ardino seems to have the highest SD values of dNBR in the fire and logging years. Ardino has a larger share of the cut forest in the second year after the fire (compared to Perperek). With the progress of vegetation regrowth processes, the SD values decreased. That is noticeable in the SD values of dDI and dNBR for Ardino and Perperek. In Bistritsa, this performance was pronounced less. The SD values for this test site remain high for dDI. Bistritsa is the test site with the lowest post-fire vegetation regrowth (Fig. 3).



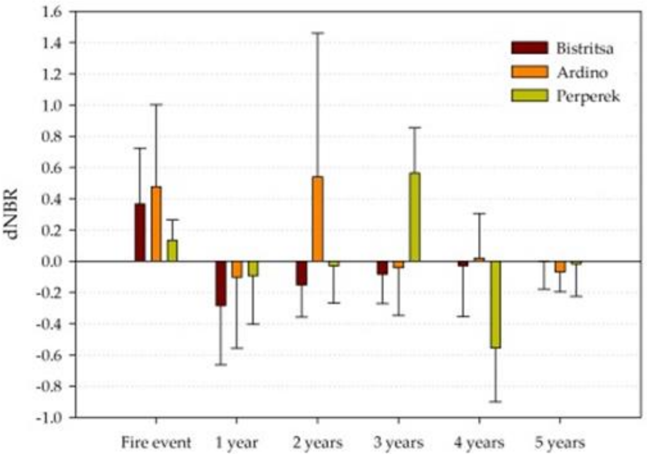
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
dNDVI
Bistritsa
Ardino
Perperek
Fire event
1 year
2 years
3 years
4 years
5 years

a)



5
4
3
2
1
0
-1
-2
-3
-4
-5
dDI
Bistritsa
Ardino
Perperek
Fire event
1 year
2 years
3 years
4 years
5 years

b)



b)

Fig. 3. SD error bars, using minimum, maximum, and mean values of dNDVI (a), dDI (b), and dNBR (c) for each of the test sites for a five-year period, starting from the fire event

Discussion

Post-fire actual state of the test sites

Due to different forest fire intensities and the influence of topographical and climatic factors on forest ecological recovery, the process of post-fire vegetation regrowth is complicated and needs accurate and in-depth studying [13]. The post-fire environment impact on forest regrowth in the three test sites was demonstrated by the performance of dNDVI, dNBR, and dDI.

The three test sites are distinguished by both environmental conditions and management practices. Bistritrishko branishte had the slowest post-fire vegetation regrowth among the three test sites. That was induced by the landscape characteristics of the area: the wetter and colder habitat, steep slopes, and shallow soils, where erosion processes are more pronounced. Even years after the fire, vegetation regrowth is slow in this test site. The vegetation is mainly represented by annual herbaceous species, whose phenological development strongly influences the indices values. This is a reason for the highly pronounced dynamics in the indices mean values in Bistritrishko branishte, associated with the seasonality of the vegetation. dNDVI had the highest mean values (0.19) in mid-summers (Fig. 2a). dNDVI mean values below zero were recorded late in the summer and early in September when herbaceous vegetation senescence and lose large part of its moisture content (Fig. 2a). This vegetation type is also strongly influenced by environmental conditions during vegetation seasons. It is less resistant to drought and other anomalies related to temperature and humidity

[14,15]. Water-limited ecosystems with low gross primary productivity, such as grassland ecosystems, show higher dependency on hydro-climatic variations, influencing vegetation greenness. They are characterized by substantial productivity decreases under drought stress, which influence their SRC [15]. This was the reason for the higher dynamics of the three studied indices in Bistrishko branishte and especially of dNDVI. Studying different grassland types, Chen et. al., 2022 [13] also confirmed a greater dependency of NDVI values on the moisture content in ecosystems and precipitation fluctuations.

Perperek test site was distinguished with the optimal condition after the fire and with the lowest damage. The sanitary logging in this test site was not significant. Burnt trees in a small territory have been removed. This fact, as well as the characteristics of the terrain, does not favor the development of intensive erosion processes, and the vegetation has better conditions to recover. Amongst the three test sites, Perperek had the optimal environmental condition for vegetation regrowth.

The Ardino test site was significantly affected by the fire, which was also the reason for the sanitary logging of a large part of the forest vegetation. This fact, as well as the landscape characteristics (steep terrain and soil erosion, slopes exposure, heat-moisture ratio), determine less favorable conditions for vegetation regrowth than those in Perperek, yet better than in Bistrishko branishte.

The results demonstrating the influence of the post-fire environment on the actual state of the forest's regrowth confirm the results of Chen et. al., 2022 [13]. Using DI as a factor removing phenological interference within the area of observation, they assessed the impact of local forest ecology on the post-fire vegetation regrowth and found a clear correlation between the index and various topographic and climatic factors. Amongst the studied factors, elevation, and slope exposure, through their influence on the heat-moisture ratio, stand out as factors with the highest impact on the forest vegetation regrowth. In mountainous areas, colder habitats are distinguished with lower recovery rates than warmer ones [13].

Performance of dNDVI, dNBR, and dDI for post-fire monitoring

Various post-fire monitoring studies have reported differences in spectral vegetation indices performance that depend on the vegetation state in the observed ecosystems. The differences in post-fire vegetation state are determined primarily by the temporal pattern of the observation (immediate post-fire observation, one and/or several years of post-fire observations), vegetation type pattern, seasonal differences, and environmental conditions. These results confirm the conclusions obtained in the present study.

Amongst the studied indices, dNDVI and dDI clearly showed disturbances in all three test sites soon after the fires (Fig. 2). The mean values of dNDVI were lowest (-0.38 in Bistrishko branishte, -0.14 in Ardino, and -0.09 in Perperek)

(Fig. 2) in these observation periods, and the values of dDI were amongst the highest (0.62 in Bistrishko branishte, 0.74 in Ardino, and 1.59 in Perperek) (Fig. 2). The only exception was dDI in Bistritsa, which recorded the highest mean values (2.16) years after the fire (01/09/2018 – 27/08/2017) (Fig. 2a). dNBR recorded its highest mean values immediately after the sanitary logging in Ardino and Perperek (0.52 in Ardino and 0.57 in Perperek) (Fig. 2b and 2c). The indices involving the SWIR band in their calculation are superior to using only red and NIR bands for monitoring forest disturbances. The logging activities and the increasing bare soils areas significantly impacted the SRC in both test sites, increasing the spectral reflectance in SWIR. The dry, bare soils and burned territories have similar signature profiles. Hence, the dNBR performance was expected. In Bistrishko branishte, such logging was not carried out, due to the protected area status.

The mean dNBR value after logging in Ardino was 0.52, and after the fire, it was slightly lower – 0.48, whereas, in Perperek, the difference between the dNBR after these two events was significant. After the logging, the mean dNBR was 0.57, and after the fire, it was barely 0.12 (Fig. 2c). The low difference between the two values for Ardino, and the large one for Perperek, is determined by the characteristics of the two fires, which differ in their intensity and damage caused. In the Ardino test site, the fire occurred in summer, and the characteristics of the terrain and weather conditions caused more significant forest damage. That led to clear-cutting in a large part of the area. In Perperek, on the other hand, the fire occurred in winter, and the terrain and wet and cool conditions supported its rapid suppression and less forest damage. The fire has affected less the forest vegetation than in the other test sites. As a result, selective logging was performed in Perperek. That influenced greater dNDVI and dDI mean values than dNBR (Fig. 2).

As expected, the highest values of dNDVI were recorded one year after the fire. At that moment, dNBR values were also the lowest (Fig. 2). That is associated with the initial rapid growth of grasses, covering the burned areas with vegetation, and the maximum change in vegetation's chlorophyll content. These results confirm the results obtained in other post-fire monitoring studies. In the following years, the indices dynamics weren't significant, and the differences between the individual test sites were determined by the differences in the ecological conditions [13] and the way the territory was regulated. dNDVI was distinguished with mean values close to zero in Perperek and Ardino test sites (Fig. 2b and 2c), which was determined firstly by the drastic reduction of vegetation after the sanitary logging, and secondly by the drier habitats. In Bistrishko branishte, where there was no sanitary logging, the values of the dNDVI showed higher dynamics (Fig. 2a), and dDI showed a greater dependence on the disturbances caused most probably by changes in environmental conditions. After the logging, the dDI values in Ardino slightly increased, while in Perperek, where the logging was significantly smaller, the index values were almost unaffected (Fig. 6b and 6c).

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НАБЛЮДЕНИЕ НА ПРИЛОЖЕНИЕТО НА СПЕКТРАЛНИ ИНДЕКСИ ЗА МОНИТОРИНГ НА ГОРИТЕ СЛЕД ПОЖАР

Д. Аветисян, Н. Станкова

Резюме

Мониторингът на нарушенията на горите след пожар и последващото възстановяване е от жизненоважно значение за целите на управлението и опазването на горските екосистеми. Това проучване има за цел да оцени щетите в горските екосистеми след пожар, както и динамиката на протичането на възстановителните процеси, използвайки данни от дистанционно наблюдение и да сравни неговата надеждност за мониторинг след пожар в различни горски екосистеми. Тази статия сравнява динамиката на възстановяване на горите, като прилага избрани спектрални индекси – Differenced Normalized Difference Vegetation Index (dNDVI), Differenced Normalized Burn Ratio (dNBR) и Differenced Disturbance Index (dDI). Направената оценка на въздействието на пожарите върху околната среда, както и процесите на възстановяване, са извършени на територията на три тестови пожара в България – Ардино, Бистришко бранище и Перперек.