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APPLICATION OF MULTISPECTRAL IMAGING IN FOREST MONITORING – A CASE STUDY OF NATIONAL PARKS IN REPUBLIC OF SERBIA

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Abstract: Deforestation and forest degradation are one of the most complex ecological challenges worldwide. Multispectral imaging and remote sensing help researchers and forest managers to quantify forest loss and degradation. By combining multiple bands of satellite data, multispectral indices can highlight changes in forest structure and reduce the cost and time required for field research. In this research multispectral indices and remote sensing are used in different areas of forestry (such as deforestation, wildfires, phenology) and five examples of remote sensing in forest monitoring are presented. The Normalized Difference Vegetation Index (NDVI) is used to quantify deforestation in ski center in Kopaonik National park. The Normalized Burn Ration (NBR) is used to assess forest fire damage in Šar planina National Park. The Soil Adjusted Vegetation Index (SAVI) is used to monitor some phenological events in Fruška gora National Park. The moisture content of vegetation in Djerdap National Park is analyzed with the Normalized Difference Moisture Index (NDMI) and pest damage is monitored with the NDVI and the Normalized Difference Red-edge Vegetation Index (NDRE) in Tara National Park. The results of these five case study analyses show that multispectral imaging provides the most evident results in monitoring deforestation, while pest and disease damage is difficult to detect.

Keywords: multispectral indices, remote sensing, forest, Kopaonik, Tara, Šar planina, Fruška gora, Djerdap

Introduction

The Food and Agriculture Organisation and the United Nations Environment Programme (2020) announced that 420 million hectares of forest have been lost

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since 1990. Three quarters of the forest loss is due to agriculture, which cuts down forests to grow crops, raise livestock and manufacture products such as paper (Ritchie, 2021).

In addition to deforestation, i.e. the loss of forests, forest degradation has also become increasingly common in recent decades. According to the International Union of Conservation of Nature, the conversion of forest to uses other than forestry is defined as deforestation, while degradation "occurs when forest ecosystems lose their capacity to provide important goods and services to people and nature" (https://www.iucn.org/resources/issues-brief/deforestation-and-forest-degradation). It refers to a reduction in forest growth or forest fruits or an imbalance in forest ecosystems. The indicators of forest degradation are diverse, such as canopy thinning, decrease in structural diversity, decrease in growth, increase in individual mortality, decrease in biodiversity (loss of important species, spread of invasive species), decrease in protective functions (e.g. increase in soil loss), decrease in production function, loss of regenerative capacity (Vásquez-Grandón, Donoso, & Gerding, 2018; Stanturf et al., 2014).

According to the European Commission's final report (2020) "Monitoring of Forests through Remote Sensing", remote sensing is used in the following areas of forestry: phenology, illegal logging, pests and diseases, forest fires, storm damage, forest drought and water content monitoring. There are numerous research papers that use remote sensing to analyse forests in the Republic of Serbia (Todorović & Gajović, 2013; Potić et al, 2017; Potić, Bugarski & Matić-Varenica, 2017; Šurjanc et al, 2019; Brovkina et al, 2020; Jovanović & Milanović 2021; Potić et al, 2022; Simović et al, 2022; Potić et al, 2023). This paper analyses the application of multispectral imaging in the research areas of deforestation, phenological events, pest monitoring, forest fires and water content monitoring using the example of five national parks in Serbia. The most valuable natural forest vegetation is found in the protected areas of national parks.

Deforestation

Remote sensing methods to detect illegal logging are mainly used in rough and large forest areas due to obstacles and difficulties in monitoring on the ground. There are numerous research works (Torres et al., 2021; De Bem et al., 2020; Cabral et al., 2018; Ortega Adarme et al., 2020) that use satellite data and different methods to detect and quantify illegal and legal deforestation in the Amazon forest, which is of great importance due to its large area and high deforestation rate, but also in terms of biodiversity conservation. The Brazilian National Institute for Space Research (INPE) has developed the DETER (Deforestation Detection in Real Time) system to monitor and control deforestation in the Amazon region since 2004. It uses the

MODIS instruments - Spectrum Radiometer of Moderate Image Resolution (http://www.inpe.br/amazonia1/en/uses_applications.php),

In the Republic of Serbia, there is no specific platform or service that provides data on legal or illegal deforestation, but there are several studies that have used remote sensing to estimate deforestation in some regions most affected by illegal deforestation, e.g. in southern Serbia (Potić et al., 2022), south-eastern Serbia (Potić et al., 2023) and Kursumlija municipality (Jovanović & Milanović 2021).

Wildfires

The European Commission (2020) recognizes three phases of forest fire monitoring:

1. Pre-fire phase (fuel mapping, fire risk assessment, etc.)
2. Active phase (fire detection, fire temperature retrieval etc.)
3. Post-fire phase (map burned areas, fire severity assessment, vegetation recovery mapping, forest restoration).

The European Forest Fire Information System (EFFIS) is one of the most developed services providing information on fire risk prediction, active fire detection, rapid damage assessment, fire damage assessment, fire emissions, forest fire risk assessment, seasonal forecast, monthly forecast, European Fire Database, fuels, etc. (https://effis.jrc.ec.europa.eu/). It is mainly based on data collected with the MODIS and VIIRS tools (European Commission, 2020).

Szpakowski and Jensen (2019) provided a comprehensive overview of remote sensing applications in different phases of fire management (fire risk mapping, fuels mapping, active fire detection, burnt area estimation, fire severity assessment and post-fire vegetation recovery monitoring). In terms of fire risk assessment and mapping, two primary methods are mentioned: point-based operational systems based on meteorological data and the use of remote sensing technologies and geographic information systems (GIS) that incorporate different variables (e.g. land cover classification, multispectral indices, altitude, slope, aspect, distance from roads and proximity to settlements). Perezo-Cabello, Montorio and Borini (2021) examined the most commonly used indices, techniques and algorithms to quantify post-fire vegetation recovery and concluded that vegetation recovery is primarily analysed using multispectral optical satellite imagery.

The information on forest fires on the territory of the Republic of Serbia is included in the European Forest Fire System. There are also numerous research works that use remote sensing to analyse and map the risk (Gigović et al., 2019; Novkovic et al., 2021) or the consequences of forest fires (Todorović & Gajović, 2013; Potic et al., 2017; Brovkina et al., 2020).

Phenological events

Bajocco et. al (2019) used text mining to analyse the number and structure of publications on remote sensing phenology between 1979 and 2018 and found 2315 scientific publications in the Scopus archive and concluded that research in the field of remote sensing phenology has increased significantly. Berra and Gaulton (2020) concluded in their review that 'at best, the timing of satellite-based phenological events on the land surface can be detected with a confidence of about half a week for spring metrics and about a week for autumn metrics".

Remote sensing for monitoring phenological events is more commonly used in the agricultural sector in the Republic of Serbia (Ljubičić et al. 2018; Pandžić et al., 2020; Ranđelović et al., 2023). There are only a few studies that analyse the phenophase of forests in the Republic of Serbia or in the region using remote sensing (Kern et al., 2017; Simović et al., 2022).

Pest and disease

There are three stages of invasion of pests and diseases in forests (European Commission, 2020; Huo, Persson & Lindberg, 2021; Luo, Huang & Roques, 2023):

1. Green attack (early stage with no visible change in the crown or tree)
2. Red attack (second stage, leaves and needles turn red or yellow)
3. Grey attack (last stage, leaves and needles lose their color and the trees die).

The European Commission's final report on forest monitoring by remote sensing states that the impact of pests and diseases can be recognised, but that there is no specific 'spectral fingerprint' to distinguish a particular pest from another health problem. Forest protection is all about early detection of pests and diseases, which is quite difficult due to the lack of visible signs of the problem. The need for very high spatial resolution data may still be the biggest obstacle for most researchers and forest managers to use remote sensing more often for pest and disease detection and control.

Remote sensing is used to detect and monitor pests and diseases in the forests of the Republic of Serbia. Simović et al. (2022) successfully used NDVI and NDRE to detect leaf miner infestation in urban forests. Šurjanc et al. (2019) used unmanned aerial systems to detect physical stress and pest infestation in forests in the Kopaonik Mountains.

Drought and water content monitoring

According to the European Commission's final report "Monitoring forests by remote sensing", most studies focus on drought and water content in relation to forest disturbance, but do not distinguish between forest and other vegetation types. Not only multispectral data are used, but also microwave satellite sensors. Most commonly, the NDVI is used to monitor the effects of drought, but there are also numerous studies using other indices (e.g. improved vegetation index, forest vulnerability index, vegetation condition index, etc.). Le, Harper and Dell (2023) identified 28 indices used to detect and monitor water stress in forests and categorised them into four groups (typical vegetation indices, water, pigment and temperature vegetation indices). They concluded that most indices use visible and infrared spectral bands and most research uses data collected by MODIS, Landsat or Sentinel satellites.

Multispectral imaging is used to monitor soil and vegetation moisture of crops rather than forests in the Republic of Serbia or the region (Potić, Bugarski & Matić-Varenica, 2017; Crocetti et al. 2020; Kostić et al., 2021, Varghese et al., 2021). Mimić et al. (2022) used the normalised differential moisture index from Sentinel-2 data to monitor moisture fluxes in several plots in the Bačka region in the province of Vojvodina and introduced a new moisture stress index for crops.

Methods and materials

Geospatial data and remote sensing are valuable resources and tools for detecting deforestation or land use change, but also for monitoring of the degradation of forest ecosystem. Lechner, Foody and Boyd (2020) recognize the scope of remote sensing application in forestry (land use/land cover, cover, vegetation structure, vegetation chemistry and moisture, biodiversity, soil, disturbance), variables (tree density, foliage projective cover, above-ground biomass, leaf area index, moisture content, individual species identification, fire scare type mapping, soil type, etc.) and technologies (multispectral fine, medium and coarse spatial resolution, hyperspectral, synthetic aperture radar, light detection and ranging).

Areas of five national parks of Serbia with emphasized study areas are shown in Figure 1. An application of remote sensing to monitor phonological events is shown using the entire area of the Fruška gora National Park as an example, while the entire area of the Djerdap National Park is used to illustrate an application of remote sensing to monitor water content. Deforestation is analyzed in a specific part of the Kopaonik National Park, and the coordinates of the studied area are 43.29182130°N and 43.27281061°N and 20.80005949°E and 20.8376076°E. An application of remote sensing in the monitoring of pests and diseases is shown using the example of a part of the Tara National Park, and the studied area has the coordinates: 43.9422111°N and 43.90346656°N and 19.41601546°E and 19.47813055°E. The forest fire in the Šar planina National Park in an area with the coordinates 42.18321116°N and 42.20527626°N and 20.83957532°E and 20.87918155°E is analyzed. All coordinates are given in the WGS84 coordinate system.

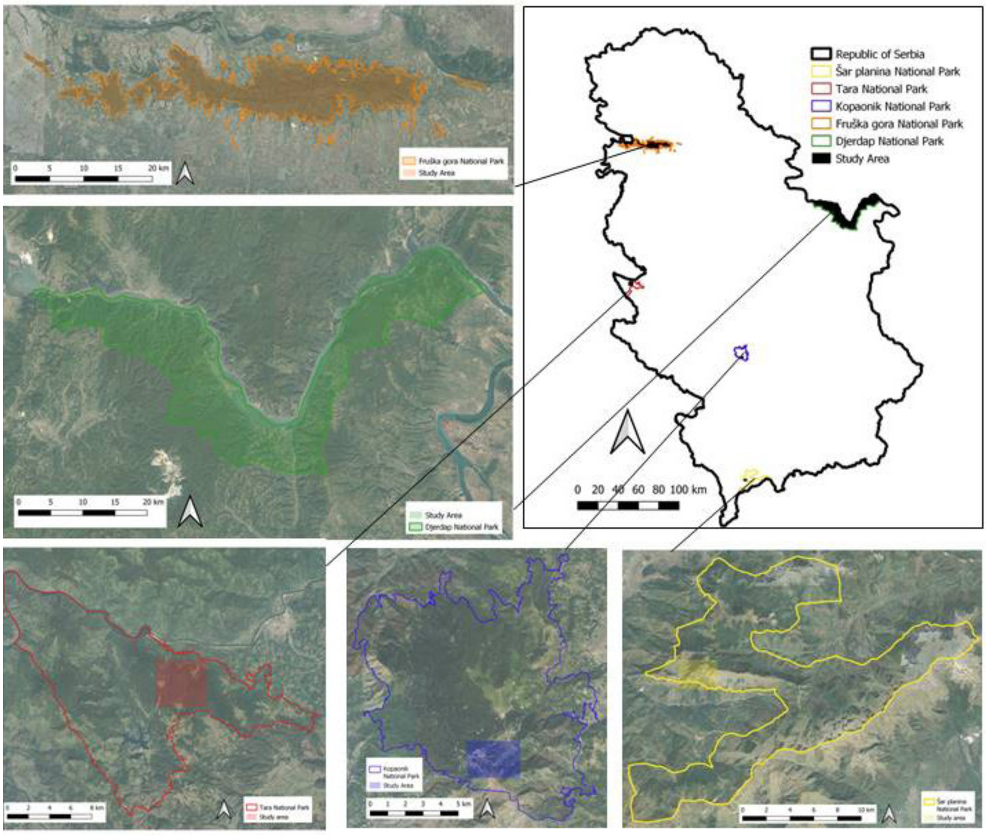

Figure 1. Geographical position of the Serbian national parks with emphasized study area
Source of basemap: Google Map Satellite activated in QGIS Hanover 3.16
Source of national parks borders : UNEP-WCMC and IUCN (2024)
Source of map: authors

The multispectral data from Sentinel 2A and Landsat 8 from the USGS Earth Explorer and Copernicus Data Space Ecosystem platforms were downloaded (https://dataspace.copernicus.eu/explore-data, https://earthexplorer.usgs.gov/). The Sentinel 2A data used in this research have a spatial resolution of 10 and 20 meters (https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/spatial), while Landsat 8 data have a spatial resolution of 30 meters (https://landsat.gsfc.nasa.gov/satellites/landsat-8/). All data are analyzed with the software QGIS 3.16 Hanover (QGIS.org, 2024).

Deforestation

In most studies using remote sensing to detect and quantify deforestation in the Republic of Serbia (Potić et al., 2022; Potić et al., 2023, Jovanović & Milanović 2021), the Normalized Difference Vegetation Index (NDVI) was used as an index indicating the change in land use/land cover. It combines the near-infrared (NIR) and the red (RED) spectrum (Rouse et al. 1974):

NDVI= (NIR – RED) / (NIR+RED) (1)

In this case study, the changes in NDVI values were analyzed for an area with deforestation and vegetation loss in the ski center in Kopaonik National Park in the period between August 2015 and July 2023. Band 8 in the near infrared and band 4 in the red spectrum of the Sentinel-2A data were used. First, the True Color Composite (TCC) was created from the data of bands 2, 3 and 4 of Sentinel 2A, which represent the visible spectrum (https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/spatial). All bands used have a spatial resolution of 10 meters. Certain dates (01/08/2015 and 20/07/2023) were selected according to cloud cover and season. To avoid or reduce the influence of phenological events and weather conditions, images without clouds and images from summer were used. After creating the TCC for 01.08.2015 and 20.07.2023, vegetation loss and deforestation were digitized and a new vector layer was created (Figure 2c). The NDVI was calculated only for the area of vegetation loss, and the changes in pixel values are presented in histograms (Figure 3).

Wildfires

The risk of wildfires in summer in the Republic of Serbia has increased due to climate change (Živanović et al., 2020) and extreme weather conditions. To present the application of multispectral data and remote sensing in the post-fire phase, the burned area in the Šar planina National Park in August 2021 is analyzed. The exact location of the forest fire was determined by the European Forest Fire Information System based on MODIS instrument data. Using the Sentinel-2 data, the Normalized Burn Ratio (NBR) for a specific area before the forest fire (30 July 2021) and after the forest fire (09 August 2021) was calculated. There was no cloud over the area on these days.

Lopez Garcia and Caselles (1991) used Landsat 5 Thematic Mapper band 4 (near-infrared) and band 7 (mid-infrared) to map the burn areas in the province of Valencia affected by the April 22, 1984 fire. Key and Benson (1999) used the same Landsat 5 Thematic Mapper bands as Lopez Garcia and Caselles (1991) and defined the Normalized Burn Ration (NBR). Key and Benson (2005) explained ordering the data (Landsat 5 Thematic Mapper), steps for processing NBR and dNBR, NBR responses, and interpretation of results. Based on the research of Key and Benson (2005), Delcourt et al. (2021) use the near/infrared and short-wave infrared spectrum of Sentinel 2 and the following equation to calculate the NBR:

$$NBR = (NIR - SWIR)/(NIR+SWIR) \quad (2)$$

$$dNBR = NBR_{pre\text{-}fire} - NBR_{post\text{-}fire} \quad (3)$$

Key and Benson (2005) emphasized that the dNBR has a theoretical range of –2.0 to +2.0, or when scaled by 10^3, –2,000 to +2,000, but in reality it is rare for valid data to vary much beyond –550 to +1,350. Declcourt et al. (2021) concluded that values of dNBR close to 0 indicating no burning, while values close to 1 indicate severely burned area (Delcourt et al., 2021). In this research band 8A as the near-infrared and band 12 as the short-wave infrared spectrum with spatial resolution of 20 meters are used.

Phenological events

The broad-leaved communities of xerophile and mesophile trees are situated in the forestland of Fruška gora National Park. Altitudes over 300 m are dominated by mountain beech forests with lime (Tilia-fagetum submontanum) (Dragićević et al., 2013). Monitoring phenology through remote sensing can help forest managers to protect trees and increase increment. In this study, we use the Soil Adjusted Vegetation Index (SAVI) to determine the difference in vegetation reflectance due to structural changes in different seasons. The influence of clouds and shadows is avoided by selecting days with little or no cloud cover and excluding all pixels in the area affected by clouds and shadows at the time of observation. In this research SAVI for the area of Fruška gora National Park on March 13, 2023, July 11, 2023 and October 23, 2023 is calculated.

Heute (1988) used SAVI to minimize the influence of soil brightness and the following equation:

$$SAVI = ((NIR\text{-}RED)/(NIR+RED+L))* (1+L) \ (3) \quad (4)$$

In the equation, NIR stands for the near infrared, RED for the red spectrum, while L is a constant that depends on the density of vegetation. Bands 4 (red spectrum) and 5 (near-infrared spectrum) of the Landsat 8 data with a spatial resolution of 30 meters are used. In this case study, the Landsat 8 data was used instead of the Sentinel 2 data because the cloud cover was lower on the observation days of the Landsat 8 mission.

Pest and disease

Bark beetles caused a forest dieback in Tara National Park in 2013, where upon pheromone traps were set up to catch the insects and control future damage (Tomic & Bezarevic., 2015). Milosavljevic et al. (2022) conducted further research on mites associated with the European spurred bark beetle (*Ips typographus)* at six sites in 2016. The locations of these pheromone traps and the number of insects caught are used to delineate the area of interest for this research. The NDVI and the Normalized Difference Red Edge Index (NDRE) for the second half of August from 2017 to 2023 are calculated. By choosing the same annual period, the influence of the phenophase on the values of the indices is avoided.The specific days without clouds and shadows over the study area are selected. The Sentinel-2 data, band 4 (red) , band 5 (near-infrared) and band 8 (near-infrared) are used and the same equation for the NDVI as in the case study of deforestation in the ski center in Kopaonik National Park.

Several equations for the NDRE can be found in the literature using similar spectral ranges, e.g. 720 nm and 790 nm (Barnes et al., 2000). In this case study, we used the equation from the study by Fernandez-Manso, Fernández-Manso and Quintano (2016), which is based on the study by Gitelson and Merzlyak (1994):

NDRE= (NIR-RED EDGE)/(NIR+RED EDGE) (5)

NIR stands for near-infrared or Sentinel 2 band 8 and RED EDGE for the spectrum of the red edge or band 5. Band 8 and band 4 correspond to a spatial resolution of 10 meters and band 5 to a spatial resolution of 20 meters. The data of both resolutions are used in the calculation, but results are only in 20 meters spatial resolution.

Drought and water content monitoring

Water deficit stress and drought in forests could create perfect conditions for wildfires and outbreaks of pests and diseases. Monitoring water content through multispectral imaging could help the forest manager to prevent damage. In this case study, we calculated the Normalized Difference Moisture Index (NDMI) for Djerdap National Park. We chose 2018 as a year with more precipitation in May, June and July and less in August, September and October to test the correlation between NDMI and monthly precipitation. To minimize the effects of cloud cover, we chose a cloud-free or low-cloud day in each month.

According to Jin and Sader (2005), the equation of the Normalized Difference Moisture Index is:

NDMI = (NIR-SWIR)/(NIR+SWIR) (6)

Where NIR stands for near infrared and SWIR for shortwave infrared. The Sentinel-2 data, band 8 as NIR and band 11 as SWIR are used. Band 8 has a spatial resolution of 10 meters, while band 11 has a resolution of 20 meters. Data of both resolutions are used, while the final result is in 20 metre resolution.

To calculate the NDMI, six (one per month) days with satellite observations with no or fewer clouds were selected. The highest values of the index were measured on May 2, 2018, the lowest on October 14 and August 20. Higher values (above 0.4) of the index indicate vegetation without water stress, while values between -0.2 and 0.4 indicate a tree canopy with water stress (https://custom-scripts.sentinel-hub.com/sentinel-2/ndmi/). There is a slight correlation between the NDMI of certain days and the monthly correlation. In further studies, dry periods or daily precipitation could be taken into account.

Results

Deforestation

Deforestation in the ski center of the Kopaonik National Park is a consequence of the development of infrastructure due to the increase in tourist activities in the winter season. Figure 2a shows the true color composite (TCC) on August 1, 2015 and Figure 1b shows the TCC on July 20, 2023. Deforestation and vegetation loss are evident. In Figure 2c, the deforested areas and the areas with vegetation loss are highlighted by a new vector layer. Figure 2d and 2e show the NDVI values of the area with vegetation loss, while the histograms (Figure 3) show that on August 1, 2015; most of the values in the highlighted area were between 0.6 and 0.8, while on July 20, 2023, the same pixels have values between 0.1 and 0.5. The values of the NDVI decreased significantly, which shows that the NDVI is suitable for detecting and quantifying deforestation and vegetation loss.

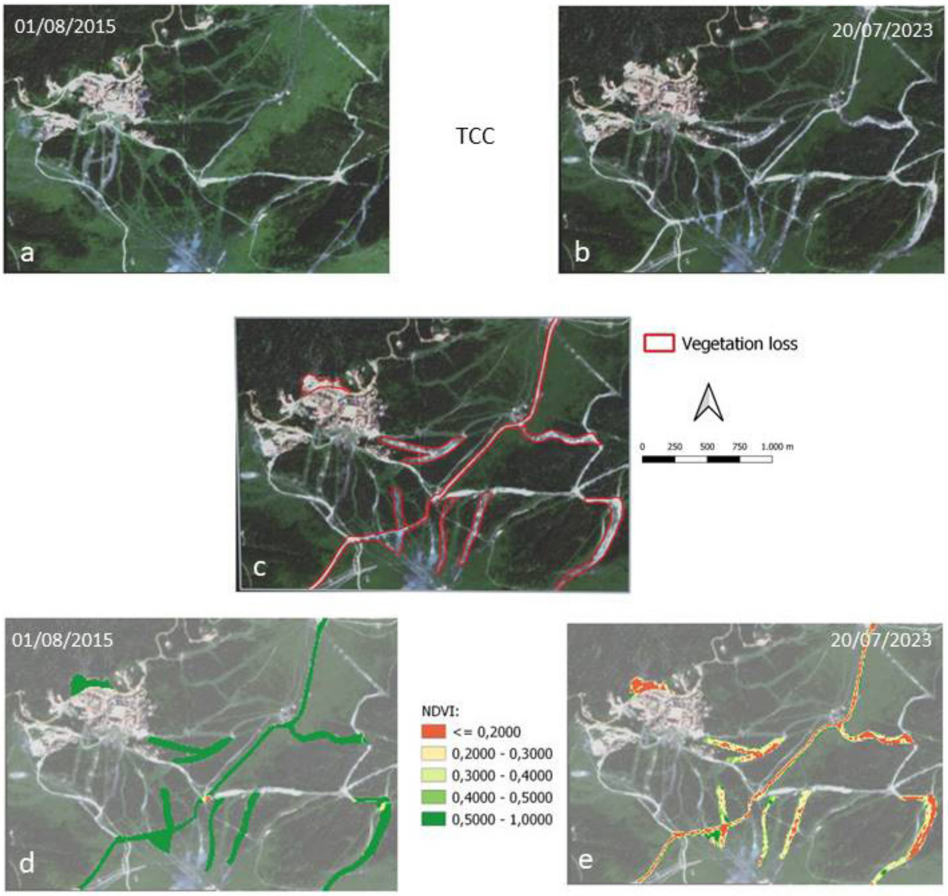

Figure 2. Ski center in Kopaonik National Park (a, b – True Color Composite, c – Digitalized Vegetation Loss, d,e – NDVI of the area of vegetation loss)
Source: authors

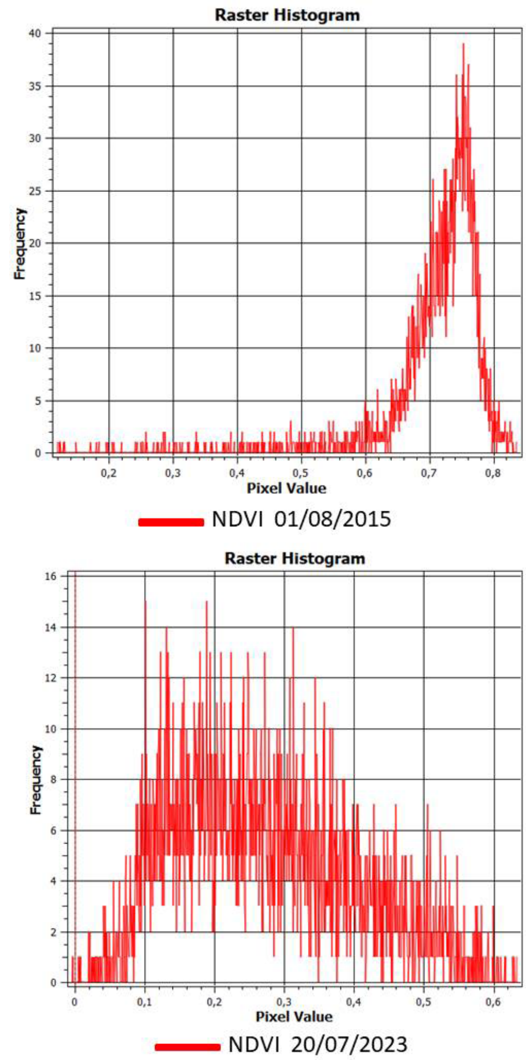

Figure 3. Raster Histograms of area of vegetation loss of ski center in Kopaonik National Park
Source: authors

Wildfires

Wildfires are a major threat to the forest ecosystem, especially in protected areas such as national parks. Mapping the burned areas is the first step in restoration management. Here the damage caused by forest fires in the western part of the Šar planina National Park has been analyzed. According to the European Forest Fire

Information System, 57 ha were affected by forest fire in August 2021, and the NBR for this area and its surroundings was calculated in this reasearch. The results are shown in Figure 4. In the analyzed area (804 ha), the values of the index after the fire were between -0.24 and 0.56, while before the fire they were between 0.02 and 0.57. Negative values of NBR (Figure 4d) indicate burnt areas. Calculating the difference (dNBR) between the NBR after and before the fire is a simple method to identify burned forest ecosystems. Positive values of dNBR (Figure 4g) indicate burnt areas.

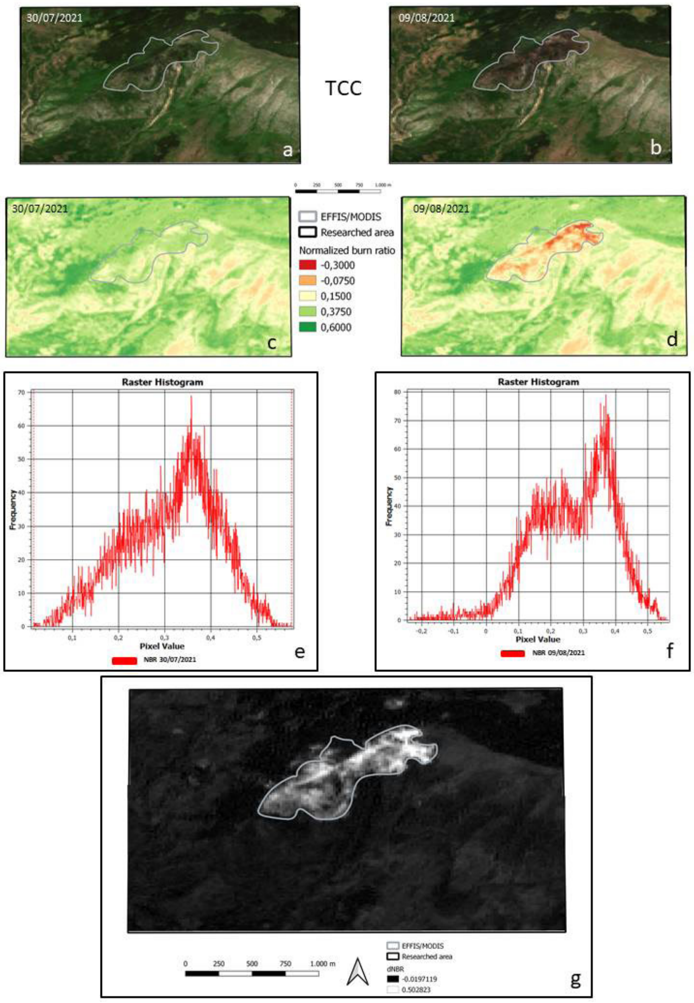

Figure 4. Wildfire in Šar planina National Park (a, b – True Color Composite, c,d – Normalized Burn Ratio, e,f – Pixel values of NBR histograms, g -dNBR)
Source: authors

Phenological events

Values of the SAVI in different seasons vary greatly due to changes in vegetation structure and cover. Figure 5 shows that SAVI values ranged from -0.08 to 0.74 on March 13, 2023, while they ranged from 0.03 to 0.78 on July 11, 2023 and from -0.11 to 0.96 on October 23, 2023 in the Fruška gora National Park. In March, however, most values were between 0 and 0.5. In the summer season they were between 0.5 and 0.75 and in the fall between 0.25 and 0.75. Further investigation could reveal more details, e.g. SAVI values in the area of dominance of certain species at the time of foliage, flowering, leaf fall, etc. The fluctuations in the index values would probably be less obvious, but valuable for forest management.

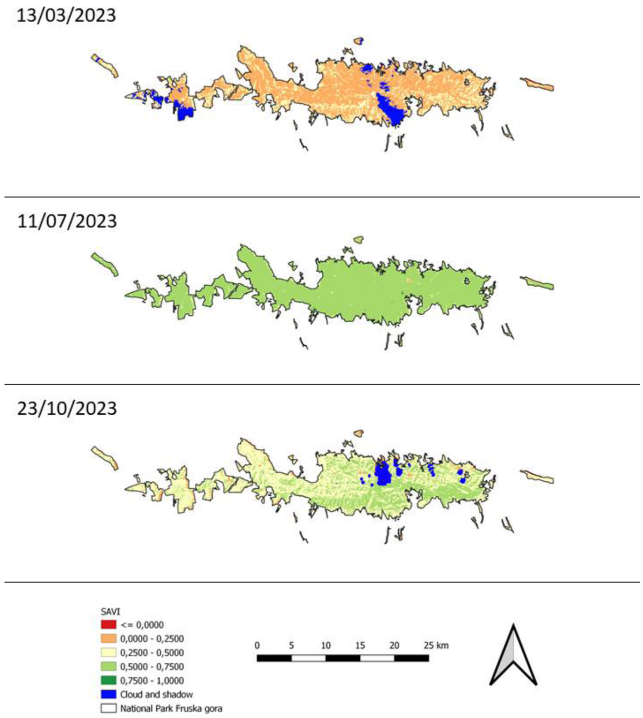

Figure 5. Soil Adjusted Vegetation Index in Fruška gora National Park
Source of Fruška gora National Park border: UNEP-WCMC and IUCN (2024)
Source of SAVI: authors

Pest and disease

Monitoring the effects of pests and diseases in the early stages requires high-resolution data as the trees partially dry out. We are trying to determine the impact of pests and diseases in the research area in Tara National Park with medium resolution data. To draw precise conclusions about drought or other damage, more detailed studies or field work are needed.

The results shown in Figure 6 show that the NDRE index reacts more sensitively to changes than the NDVI index. Figures 6a and 6b, created in QGIS Hannover 3.16, show the boundaries of the Tara National Park and the study area. The satellite base map activated in the software (Layer/Add Layer/Add XYZ layer/Satellite) contains different brightness levels in some parts of the area shown, without specific reasons, which becomes clearer at a higher zoom level (Figures 6b, 6c and 6d).

As can be seen in Figure 6c and 6d, the values of both indices were highest on August 25, 2017, while they were lowest on August 29, 2022. Higher values of both indices indicate better vegetation condition. Lower values indicate drier vegetation. Dryness could be a result of pest infestation, drought or other stress. For pest and disease infestations, low scores should appear as patches and spread over time if forest managers do not respond. In this case study, field work or more detailed analyses are needed to clarify the reasons for the low NDVI and NDRE values in the last two years of the observation period.

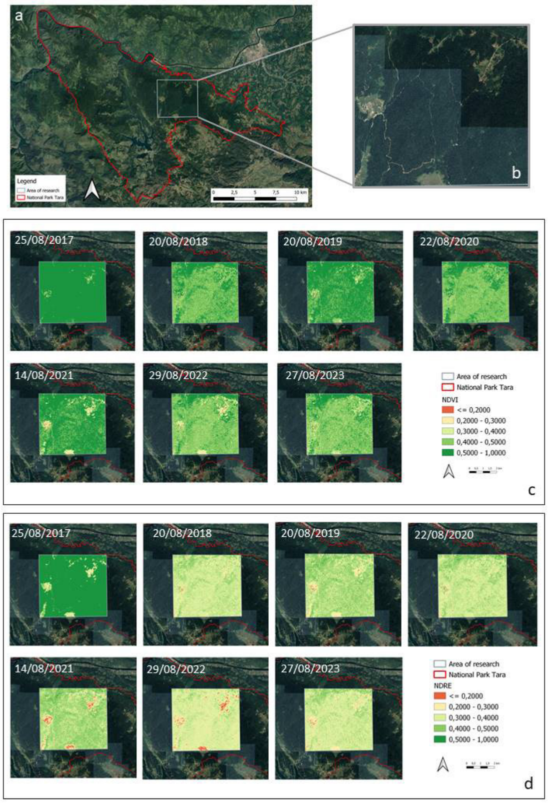

Figure 6. NDVI and NDRE in Tara National Park (a,b – borders of area of research, c – Normalized Difference Vegetation Index, d – Normalized Difference Vegetation Index Red Edge)

Source of basemap: Google Map Satellite activated in QGIS Hanover 3.16
Source of Tara National Park border: UNEP-WCMC and IUCN (2024)
Source of NDVI and NDRE: authors

Drought and water content monitoring

The territory of Djerdap National Park is covered with more than 50 phytocenoses, among them communities with *Quercus frainetto* and *Q.cerris* on silicates and *Q.cerris* with *Carpinus orientalis* on limestone, are dominant (Dragićević et al., 2013). Water deficits could destroy the trees or reduce their natural ability to cope with pests and diseases. In 2018, the Veliko Gradište meteorological station recorded the most precipitation in June (205.9 mm) and the least in October (12.7 mm). Less precipitation fell in September (20.1 mm) and August (27.2 mm), while 106 mm (41 mm) was recorded in May (Republički hidrometeorološki zavod, 2019). Figure 7 shows the climate diagram and the NDMI values on certain days. The lowest NDMI values were calculated on August 20, 2018 and October 14, 2018.

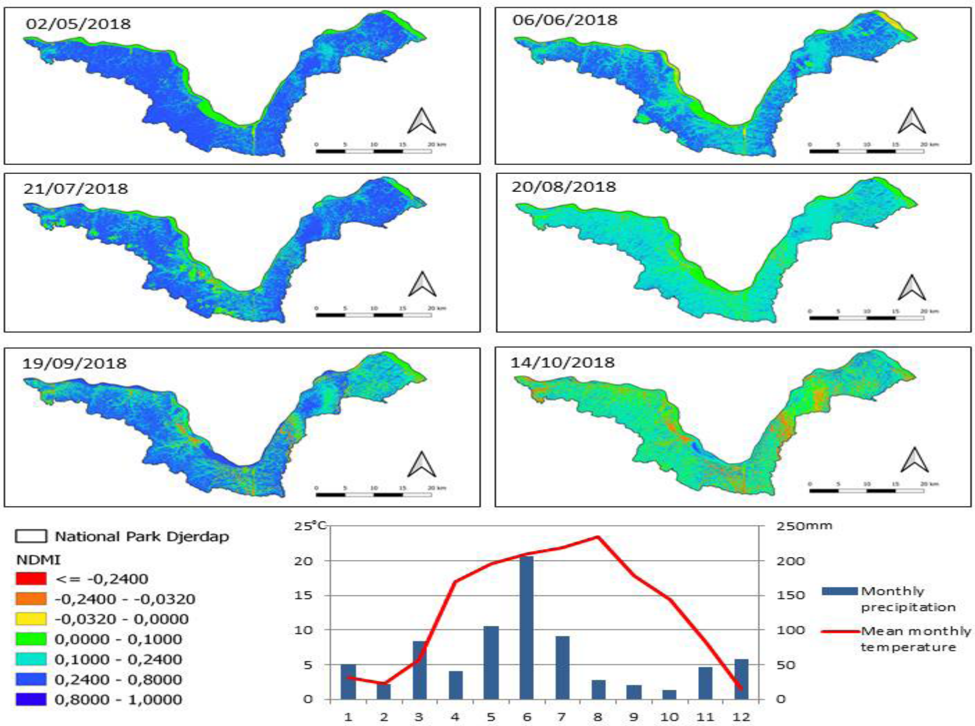

Figure 7. Normalized Difference Moisture Index and Climate diagram (Veliko Gradište, 2018)
Source of Djerdap National Park border: UNEP-WCMC and IUCN (2024)
Source of precipitation and temperature data: Republički hidrometeorološki zavod (2019)
Source of NDMI: authors

Discussion and conclusions

The most visible changes in the forest are those that can best be detected and monitored by remote sensing and multispectral imaging. Deforestation and wildfires change the values of light reflected by vegetation in such a way that medium-resolution satellite images and the most common indices (e.g. NDVI) are sufficient to quantify the damage. More specific indices (e.g. NDRE, NDMI) are required to monitor water stress and phenological events. Remote sensing and multispectral imaging are suitable tools for monitoring seasonal changes in vegetation.The biggest challenge is to detect pest and disease infestations, and these changes are usually only visible with high-resolution satellite imagery or at a time when the damage has already had a major impact.

Continuous remote sensing of forests can help managers to protect the ecosystem, preserve biodiversity and increase vegetation growth. It requires fewer resources and less time than traditional on-site monitoring. Commercial satellites that take very high resolution images or unmanned aerial vehicles are better suited for more detailed analysis. In the future, combining the results of monitored changes with machine learning and artificial intelligence may lead to the development of accurate models that help forest managers to prevent drought, wildfires or pest and disease infestations.

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Satellite data used in case study analysis were downloaded from Copernicus Data Space Ecosystem and USGS Earth Explorer:

https://dataspace.copernicus.eu/explore-data

https://earthexplorer.usgs.gov/