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POST-FIRE RECOVERY MONITORING USING REMOTE SENSING: A REVIEW

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Abstract

Wildfires are a common disturbance factor, while climate change is thought to be one of the main causes of the fires. The detection of disturbance and post-fire recovery monitoring are vital for ecological research. This article aims to provide a review of current research of post-fire recovery monitoring based on remotely sensed data. While a close relationship between vegetation indices (VIs) and physiological parameters of vegetation has been established, VIs have become the main tool for assessing and monitoring vegetation status. Research on the effects and recovery from fires has been conducted by a number of authors, with VIs being used mainly in the methodologies. Tasseled Cap Transformation (TCT) method is also used to assess the state of the ecosystem before and after a fire. When viewed in series, Disturbance Index (DI) images provide an immediate way to recognize the pixels of the forests affected by the fire, different from those characteristics of the normal state of forests. The incorporation of various remote sensing data with field data is able to support the monitoring of post-fire effects and forest recovery.

Introduction

Monitoring the recovery processes of burned forests is a bit more complicated task than identifying them, mainly due to the smaller scale of the recovery areas compared to the total area, and due to the fact that the change in the signature may be barely noticeable, especially in the initial recovery stages. Fire creates heterogeneity on the landscape, which impacts the dynamics of the forest regrowth process. Recovery in areas partially affected by fire can be difficult to detect.

In the last few years, when the consequences of the forest fires in some regions of Bulgaria reached enormous dimentions, more detailed studies began [1–5].

Ecological framework

The ecological consequences of forest fire are multifaceted – deforestation and soil erosion, change in water flow, disruption of the heat and water balance of ecosystems, destruction of unique habitats of rare, protected, and endemic species, biological diversity limitation, deterioration of sanitary conditions of forests, disrupting the CO_2 cycle in nature.

The damage in terms of biodiversity loss and soil erosion is practically irreversible. The main fuel for wildfires consists basically of vegetation, while large fires can leave an entire area without vegetation cover, which can lead to significant climatic, ecological, and hydrological risks. In addition, after a fire, plant communities can be replaced by new different types of communities, which is due to invasive species, as a result of the variety of secondary effects that occur. When the vegetation cover is burned, almost all environmental conditions change. Forest fires destroy vegetation, animals, and microorganisms, which are necessary for the normal function of the cycle in living nature. It also destroys the soil humus, thus disrupting homeostasis, i.e. the sustainability of ecosystems.

After a fire, the amount of light on the soil increases. That is why the first species that settle on the burnt areas are the light-loving ones. The lack of plant cover increases the direct penetration of precipitation into the soil and disturbs the water balance. Waterlogging of the soil and the appearance of erosion processes are possible. A forest fire primarily burns the undergrowth and also destroys the seed stock. The fire burns the forest floor, which leads to destruction of the numerous micro- and macro-organisms, inhabiting the surface layer of the soil [4].

In the areas that are prone to forest fires, where fires are a constant phenomenon, many tree species (pyrophytes) have adapted to the effects of fire and successfully survive. Their seeds have a hard and strong shell that protects them from fire and preserves their ability to germinate. As a rule, pyrophytes are fast-growing species and begin to bear fruit early. Some tree species contain in their leaves a little burning substances and a greater water content, which is also an adaptation to reduce the destructive effect of fire and its limitation.

Unlike pyrophytes, coniferous species contain a lot of resinous substances, which contributes to their rapid burning and the damage from fires is significantly greater. Beech (*Fagus*), fir (*Abies*), spruce (*Picea*), Balcan pine (*Pinus Peuce),* birch (*Betula alba*), and aspen (*Populus tremula*) tree species have thin bark that burns easily and is quickly damaged by fire. In contrast, oaks (*Quercus*), black pines (*Pinus nigra*), larches (*Larix*) have thick bark, which makes them resistant to ground fires. Important for the resistance of tree species against fires is the presence of dormant buds, especially when they are on the root system. Aspens, hornbeams, beeches, lindens, etc. have the ability to give many root shoots [4, 5].

Forest fires lead to soil degradation, which is expressed in the reduction of its nutrient supply (burning of organic matter, reduction of nitrogen content, change in the content and ratio between the total and exchangeable forms of nutritional elements) and development of erosion. It has been established that about three years after a fire, the limitation of degradation processes begins, expressed mainly in the levels of soil indicators to those before the fire.

In cases where, as a result of a fire, there is a real supply of nutrients in exchangeable forms, it is possible for them to be adsorbed by the plants, and after decomposition of the leaf mass – to fall into the soil again. The temporary accumulation of nutrients facilitates rapid vegetation recovery. If the frequency of fires is high, as observed in some areas, the food supply of the ecosystems is not fully restored. The long-term post-fire effect for our geographical latitudes and climatic conditions is expressed in a gradual reduction of soil nutrient reserves, a slowing down of the rate of vegetation recovery, an intensification of erosion processes, which in turn lead to irreversible desertification processes.

The consequences of forest fires continue for decades, and in our climatic conditions they almost always lead to negative consequences in terms of the productivity of ecosystems, including tree stands. In addition to damaging ecosystems, wildfires create conditions that favor the occurrence of new fires. This is due to a violation of the integrity of the forest, which on one hand leads to a disturbance of the microclimate and a decrease in moisture, and on the other – allows the appearance of grasses, lianas, and bushes, thus increasing the amount of light, easily flammable combustible materials.

The assessments obtained by remote sensing methods for the heterogeneity and spatial distribution of burned areas were also used to identify priority areas for fuel reduction and post-fire recovery. Post-fire recovery of forests depends on adequate seed dispersal and favorable microclimate conditions, which in turn are related to the location and type of landscapes (height, slope, and aspect). Large areas with high burn severity may have fewer surviving trees to provide seeds. Unburned or areas with low burn severity within high burn severity areas can provide sources of seed to increase the rate of forest recovery. After a fire, the environment can change significantly within a year and some aspects may be predictable, while others may depend on local weather conditions.

Passive and active sensors

In terms of the remote sensing of post-fire effects, we can divide the available sensor systems into passive and active. The most commonly used type of active sensor being used to evaluate fire-related information is light detection and ranging (Lidar) systems. These provide information on the elevation (and thus relative height) of a surface by measuring the time taken for a pulse of laser light to journey between a sensor and a surface. Lidar systems are predominately aerial-based and have been widely used to characterize individual-tree and stand-level canopy structure. Spaceborne SAR data also provides an alternative approach for monitoring the regrowth of post-fire forests, since backscatter is also sensitive to forest structural parameters. The majority of remote sensing systems that have been used to infer post-fire characteristics have been passive sensors measuring the reflection or emission of electromagnetic radiation from surfaces. Multispectral airborne and satellite sensors use radiometers that are sensitive to narrow bandwidths (bands) of the electromagnetic spectrum.

VIs

Research on the effects and recovery from fires has been conducted by a number of authors, with VIs being used mainly in the methodologies. VIs are usually dimensionless quantities obtained by satellite data in different spectral ranges, mainly used to show the amount of green vegetation available. Due to this fact, VIs have become the main tool for assessing and monitoring vegetation status. A close relationship between VI and physiological parameters of vegetation (LAI, biomass, photosynthetic activity, productivity, etc.) has been proven. Although LAI is the major morphological parameter of vegetation cover associated with satellite VIs, its measurement and assessment are very complex. For this reason, VIs are appropriate indicators for monitoring and assessment of vegetation condition.

Although one of the first, Normalized Difference Vegetation Index (NDVI) [6] is one of the most commonly used VIs for assessing green vegetation biomass as well as for remote assessment of recovery processes of vegetation after fire. A study by Chèret and Denux [7] found that changes in NDVI values correlated with the De Marton Drought Index. The spectral reflective characteristics of vegetation in the visible and near infrared range, in contrast to those of the soil, explain the use of NDVI to distinguish vegetation cover. In addition, NDVI partially normalizes the influence of external factors in the reflection of vegetation, i.e. errors associated with changes in illumination or atmospheric scattering.

As the processes of vegetation and drought are not very dynamic, the data with average spatial resolution are more suitable for detailed studies of small areas. What is specific is that the VIs based on optical data are particularly sensitive to the presence of any clouds. To be correctly determined, it must be ensured that the cloud cover is zero over the studied area. When using low-resolution satellite data, there is a risk of cloud cover for some parts occupying an area of less than one pixel of the image. In this case, NDVI index is artificially lowered. To avoid this, indices are used that are formed by channels with a longer wavelength (EVI, NDWI or NDII).

Normalized Difference Water Index ($NDWI_{1.24\mu m}$) [8] uses a wavelength in the mid-infrared range, less affected by atmospheric absorption. $NDWI_{1.64\mu m}$ shows less saturation than $NDWI_{1.24\mu m}$.

Normalized Difference Infrared Index (NDII) is used analogously to NDWI when lacks data in the SWIR range [9].

Normalized Multi-band Drought Index (NMDI) is used simultaneously to study the dryness of the soil layer and the moisture content in the leaf mass of plants [10]. This improved drought index is able to calculate the water content of both soil and vegetation and is therefore expected to offer more accurate estimates of the degree of drought and the impact of fire [10].

Normalized Difference Dust Index (NDDI) is used to study the effect of soil and leaf drought on the vegetation process of plants, as well as the effect of fires on vegetation [11].

Enhanced Vegetation Index (EVI) [12] is used similarly to NDVI for the study of vegetation, as the lower the value, the less the vegetation and the leaf mass of plants. The decrease of the index over the years signals deforestation of a given area [9]. Unlike NDVI, this index is less sensitive to the presence of scattered clouds or small dust particles in the atmosphere, which reduce the radiation reflected by the object reaching the sensor.

Moisture Stress Index (MSI) is used to determine the stress in vegetation, measured by changes in moisture content [13].

Soil-Adjusted Vegetation Index (SAVI) uses an L-factor to correct the different reflectivity of soils [14]. SAVI is more closely related to LAI than to NDVI.

An alternative approach to soil line correction is the Perpendicular Vegetation Index (PVI) [15]. PVI is interpreted geometrically as the perpendicular distance of a measured point from the soil line. The perpendicular distance of the R/NIR measurement from the soil line is not linearly related to LAI.

The fire impacts are assessed significantly more frequently by the Normalized Burn Ratio (NBR) index [16], which using the near and middle infrared channel is designed to be maximally sensitive to overall changes in spectral reflectance characteristics caused by fire. Differenced Normalized Burn Ratio (dNBR) is the result of differences in NBR index before and after fire. NBR and dNBR are key indicators of burn severity and can be used to determine post-fire effects, fire size, and burn severity classifications. NBR is also used for the degree of post-fire recovery. The dNDVI and dNBR indices are distinguished by higher map accuracies and regression relationships in forested areas, compared with results for studies conducted in environments with lower gross primary productivity.

The Mid-infrared Bispectral Index (MIRBI) was created to assess the burnt vegetation in the savanna [17]. Although MIRBI was developed only to assess burned vegetation, NBR and dNBR have been widely used to assess post-fire landscape effects in the USA, as well as in South African savannas. In addition to measuring burned vegetation, NBR is used to measure the extent of ecological change after a fire.

Terrestrial data on post-fire effects include assessment of soil color change; soil infiltration and hydrophobicity; the change in plant char and ash cover; tree scars and organic fuel consumption.

In an attempt to integrate these different measurements, Key and Benson [18] developed the terrestrial Composite Burn Index (CBI). CBI is based on a visual assessment of the amount of burned vegetation, the degree of soil charring and the degree of vegetation regeneration. The CBI was established for the purpose of ground validation of the NBR spectral index. After the effects of the fire on 30 m x 30 m test plots in five separate horizontal layers (from soil to tree crowns) were assessed separately and then combined into one total "burn severity" value for the plot. The CBI method is quite fast but very subjective.

The presence of areas with similar environments, behavior and post-fire impacts has led to the use of the term "severity classes" within both the ecological literature and remote sensing. And yet there are significant variations in the so-called “low”, “moderate” and “high” degree of classification depending on the region and types of vegetation. In forested areas, remotely sensed “burn severity” maps often show a strong correlation with fire effects on the upper canopy and exhibit low correlation with terrestrial and soil variables where vegetation obscures the ground.

The use of temporal series and transformations are widespread. Remote sensing with time series data offers considerable potential in the trajectory of post-fire forest dynamics, beyond monitoring forest succession and current structural attributes of forests after fires. Many studies have addressed this issue by using moderate-to-low resolution time series NDVI, SAVI, EVI, albedo, NDVI-based Net Primary Productivity (NPP), fraction of absorbed photosynthetically active radiation (fAPAR) and, recently, the vegetation optical depth (VOD) parameter from the Advanced Microwave Scanning Radiometer for Earth Observing System (EOS) (AMSR-E) sensor as surrogates representing the recovery of vegetation after fire disturbances.

TCT

The model for orthogonalization of satellite images proposed by Kauth and Thomas [19] is a very effective method for interpretation, classification and analysis of phenomena and processes related to the dynamics of the main components of the earth's surface – soil, vegetation, and water. This type of transformation is called Tasseled Cap Transformation (TCT) [19]. The method used for linear spectral transformation in multidimensional space to reduce the correlation between its individual elements using three components – soil, vegetation and humidity – is also used to assess the state of the ecosystem before and after a fire. TCT is related to the change of the coordinate axes in the spectral space from the original ones in three uncorrelated directions, preserving their orthogonality – Brightness (TCB), Greenness (TCG) and Wetness (TCW).

The TCB index is the sum of all channels corresponding to the direction of the main change in soil reflection. The TCG index represents the contrast between the infrared and the visible channel, orthogonal to the TCB. The TCW index refers to plant and soil moisture, orthogonal to the TCB and TCG. Different sensors use different transformation matrices, fixed only for them.

Healey et al. [20] calculated Disturbance Index (DI), which is a linear combination of the three Tasseled Cap indices. The calculation of DI is based on the observation that burned forests are usually characterized by higher values of the TCB and lower values of the TCG and TCW compared to unaffected forest areas [20]. However, as there are variations that exist in the acquisition date between images, the detection index adopted should be relatively insensitive to the Bidirectional Reflectance Distribution Function variability and phenology. Thus, spectral normalization of the TCB, TCG, and TCW indices should be performed which use within-image statistics to normalize radiometric change. Therefore, the areas affected by the fire have high positive nTCB values and low negative nTCG and nTCW values (where the prefix “n” stands for “normalized”). They show high DI values. Conversely, unaffected areas should present low DI values [20]. DI quantifies how close the pixel is to an area in the scene, characterized by the highest TCB and the lowest TCG and TCW indices. When viewed in series, DI images provide an immediate way to recognize the pixels of the forests affected by the fire, different from those characteristics of the normal state of forests.

Conclusion

Aerospace remote sensing methods are a high-tech tool for reliable and large-scale monitoring of recovery processes in forest ecosystems after a fire. The study of the consequences of forest fires is determined by their large-scale and long-lasting effects on the ecological situation of huge territories. For operational, reliable, and large-scale research, remote aerospace methods and technologies are vital. Incorporation of various remote sensing data with field data is able to support the monitoring of post-fire effects and forest recovery.

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МОНИТОРИНГ НА ВЪЗСТАНОВИТЕЛНИТЕ ПРОЦЕСИ СЛЕД ПОЖАР С ИЗПОЛЗВАНЕ НА ДИСТАНЦИОННИ МЕТОДИ: ПРЕГЛЕД

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Резюме

Откриването на засегнати територии и мониторингът на възстановителните процеси след пожар са жизненоважни за екологичните изследвания. Тази статия има за цел да направи основен преглед на текущите изследвания на мониторинга за възстановителните процеси след пожар въз основа на данни от дистанционно наблюдение. Тъй като е установена тясна връзка между вегетационните индекси (ВИ) и физиологичните параметри на растителността, ВИ се превръщат в основен инструмент за оценка и мониторинг на състоянието на растителността. Изследвания върху ефектите и възстановяването от пожари са проведени от редица автори, като в методологиите им се използват главно ВИ. Методът Tasseled cap трансформация (ТСТ) също се използва за оценка на състоянието на екосистемата преди и след пожар. Разглеждани последователно, DI изображенията осигуряват начин за разпознаване на пикселите на горите, засегнати от пожара, различаващи се от тези, характерни за нормалното състояние на горите. Обединяването на различни данни от дистанционно наблюдение с полеви данни е в състояние да подпомогне мониторинга на последствията след пожар, както и последващото възстановяване на горите.