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DETECTION AND ASSESSMENT OF ABIOTIC STRESS OF CONIFEROUS LANDSCAPES CAUSED BY URANIUM MINING (USING HYPERSPECTRAL EO-1/HYPERION DATA)

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Abstract

The paper presents the results from a study aiming at detecting and assessing abiotic stress in coniferous landscapes of Black pine monocultures (Pinus nigra L.) by using ground-based geochemical data, models of technogenic pollution, and satellite hyperspectral data from EO-1/Hyperion. Four vegetation indices (VIs), such as, MCARI, TCARI, MTVI 2, and PRI, as well as the shape and area attributes of the red-edge spectral features, have been studied in order to detect changes caused by the geochemical pollution. The analysis was performed on 4 test sites sized each 30m × 30 m, to correspond to EO-1/Hyperion pixel subspace, in homogenous coniferous landscapes in the Teyna River basin – a left tributary to Iskar River. In effect, the red-edge position index for unstressed coniferous landscapes (Black pine) was found to be at about λ=683 nm, whereas the stressed ones' red-edge position is at λ=671 nm. It was found that VIs, such as TCARI/MCARI and Z_c *has highest correlation (*r^2*=0.63; F: 5.20 at F: <0.1), followed by MTVI 2 and* Z_c *(*r^2*=0.42; F: 2.48 at F: <0.21), and PRI and* Z_c *(*r^2*=0.30; F: 1.34 at F: <0.33). Subsequently, the four test sites chosen were subdivided in two pairs, corresponding to the modeled* Z_c *values after Inverse Multiquadratic Function (IMF) from the set of Radial Basis Function (RBF), into unstressed (test sites No. 2 and No. 5) and stressed coniferous landscapes (test sites No. 10 and No. 11). The hypothesis tested is that the clustering of EO-1/Hyperion VIs corresponds to* Z_c *clustering using hierarchical clustering method (Ward). As a result, the MTVI 2 and TCARI/MCARI values group their first cluster relatively farther than* Z_c *but the PRI does not reflect the* Z_c *clusters. This lead to the conclusion that the satellite hyperspectral narrowband VIs are still not sensitive enough to study the geochemical background and vegetation stress of geochemically stressed coniferous landscapes by uranium mining without a priori ground based data.*

1. Introduction

Nature features cannot be measured directly by remote sensing. Usually the reflectance in different spectral bands is correlated with ground-measured forest attributes (Dimitrov and Roumenina, 2012). By the incremental and non-specific changes in those forest characteristics it is possible to detect negative and positive changes. From botanist point of view it is accepted that plant stress is: "state in which increasing demands made upon a plant lead to an initial destabilization of functions, followed by normalization and improved resistance" (Lichtenthaler, 1996). Furthermore, "If the limits of tolerance are exceeded and the adaptive capacity is overworked, the result may be permanent damage or even death" (Larcher 1987; Lichtenthaler, 1996). The plant stress is further differentiated by its driving force, direction (positive or *eu-stress* and negative *dis-stress*), phases (*response*, *restitution*, *end*, and *regeneration* phase) and the scale of its impact (Lichtenthaler, 1996). A classification of the abiotic stressors and their impact on the spectral characteristics of coniferous vegetation at particular wavelengths of the spectrum has been done recently (Jones and Schofield, 2008). In present study the studied stress driving factors are: heavy metals and natural radionuclides. The possible use of hyperspectral satellite missions such as CHRIS/PROBA (ESA) and EO-1/Hyperion (NASA) for forest monitoring and chemical vegetation stress have been addressed in several publications recently (Peddle *et al*, 2008; Filchev, 2013; Filchev and Roumenina, 2013). However, the still experimental technology and the limited capabilities of the hardware, including telemetry, calibration, as well as the high volume of data coming from hyperspectral sensors, are still preventing the widespread use of hyperspectral data.

The motivation for the study is based on the fact that coniferous forests in Bulgaria cover over 1.2 million ha, which represents 31 % of the forested area (NSI, 2008; Dimitrov and Roumenina, 2012). Furthermore, during the past decade in Europe have been implemented a series of projects under FP6 and FP7 as well as on national levels which deal with the utilization of hyperspectral remote sensing data for detection of stress and monitoring of pollution in mining environments (Filchev and Roumenina, 2013). In Bulgaria the potential use of multispectral and hyperspectral Remote Sensing (RS) satellite and airborne data, for detection and assessment of pollution from mining, has been studied since the beginning of 80s of 20^{th} century (Mishev *et al*, 1981, 1987; Roumenina, 1991; Spiridonov *et al*, 1992; Velikov *et al*, 1995). For studying the level and the pathways of the pollution of the soil-vegetation system in the vicinity of former *Devnya* enterprise, *Kremikovtzi* metallurgic enterprise, and *Kardzhali* metallurgic enterprise were created landscape maps with the use of multispectral images from MKF-6M and panchromatic images from MRB, onboard of AN-30, as well as from the satellites ERTS, Landsat and Salut 4. In order to study the level of the anthropogenic load is used the coefficient of technogenic load or concentration - K_c, which is also used in present study. Later on, geoinformation technologies are used in ecological risk assessment and health assessment of the spruce forests of *Chuprene* Man And Biosphere (MAB) UNESCO reserve (Roumenina and Dimitrov, 2003; Roumenina *et al*, 2003). The interest in studying the effects from geochemical pollution had gained momentum and was continued and further developed by employing field spectrometry data in the works of (Nikolov *et al*, 2005; Kancheva and Borisova, 2005, 2007, 2008; Kancheva and Georgiev, 2012; Filchev and Roumenina, 2012, 2013).

The objective of the study is to detect and assess abiotic stress of coniferous landscapes, composed of monoculture European Black pine forests (*Pinus nigra L.*), caused by uranium mining by using hyper spectral Earth Observing (EO)-1/Hyperion satellite data and ground based geochemical data.

1.1. Study area

The study area comprises the river basin of the *Teyna* River. It is located between 42°50’N and 40°51’N latitude and 23°19’E and 23°20’E longitude and occupies an area of 4,775 km^2 with altitude varying from 500 m a.s.l. at the influx of the *Teyna* River into the *Iskur* River to 964 m a.s.l., i.e. the highest parts of the water-catchment (Filchev, 2009; Filchev and Yordanova, 2011; Filchev and Roumenina, 2013). The dominating vegetation type is presented by mono-culture plants of Scots pine (*Pinus sylvestris L.*) and European Black pine (*Pinus nigra L.*) in the place of the natural oak (*Quercus sp.*) (Bondev, 1991; Filchev and Roumenina, 2013).

Iskra uranium mining section:

The *Iskra* uranium mining section is located in the river basin of the *Teyna* River (area 4.87 ha) (Roumenina *et al*, 2007; Naydenova and Roumenina, 2009). Within the section were developed 12 embankments, 1 quarry, and 2 technological sludge pans. In 1956 after open-pit mining technique started the development of the deposit. The classical mining in the section ended in 1962. In 1984 geotechnological mining was started, and was decommissioned in 1990. The technological liquidation, biological restoration, and reclamation started after 1994 based on Decree No.163/20.08.1992 of the Council of Ministers and Order No.56 of the Council of Ministers from 29.03.1994 (Simeonova, Ignatov, Mladenov, 1993; Banov and Hristov, 1996; Naydenova and Roumenina, 2009). The environmental conditions in the studied region were additionally complicated by the correction of the river bed which caused almost total draining of the surface waters through adits in the *Kisseloto ezero* (Filchev and Yordanova, 2011).

2. Materials and methods

2.1. Data

In this study two types of data are used – ground-based and satellite data.

Ground-based data:

During the ground-based studies conducted in 2010–2011 on the *Iskra* mining section, the following data were collected: GPS measurements for more accurate georeferencing of the satellite data. The test sites were sized 30m × 30m, which is the ground projection of EO-1/Hyperion pixel (Filchev and Roumenina, 2013). The assessment of the geo-chemical condition of the test area was based on an archive data and published articles, (Simeonova, Ignatov, Mladenov, 1993; Banov and Hristov, 1996; Georgiev and Grudev, 2003).

Satellite data:

One scene from the EO-1/Hyperion satellite spectroradiometer acquired in 21 August 2002 (ID EO1H1840302002233110PZ), distributed by the United States Geological Survey (USGS), was used. The EO-1/Hyperion data is distributed in Hierarchical Data Format (HDF) 4.1 (or 5 edition) or Geographic Tagged Image-File Format (GeoTIFF) recorded in band-interleaved-by-line (BIL) files. The data quantisation (digital numbers – DN) is 16 bits and the scene total width is 7.5 km and the length is 42 кm. From 242 bands in the spectral region: (λλ 357 ÷ 2576 nm), 220 are unique, i.e. they do not spectrally overlap. Fully calibrated are 198 bands but due to the overlap in the Visible and Near InfraRed (VNIR) their number is reduced to 196 bands. The calibrated bands are respectively, from 8^{th} to 57^{th} band in the VNIR and from 77^{th} to 224^{th} for the Shortwave InfraRed (SWIR). With the increase of the wavelength (λ) Signal-to-Noise Ratio (S/N Ratio) of the EO-1/Hyperion decreases from 190:1 to 40:1

(Pearlman, Segal et al. 2000). The scene under investigation represents the study area 10 years after uranium mine decommissioning. The satellite data and the vector layers used in the analysis were transformed into World Geodetic System (WGS 84) datum, Universal Transverse Mercator (UTM), Zone 35N projection. The 16-bit integer values of the .hdf files were converted into spectral radiances (Beck, 2003). This was followed by selection of EO-1/Hyperion spectral channels 6–57 and 77–92, which are calibrated and correspond to ASD HH FS Demo 1445 spectral range used in previous study of the authors (Filchev and Roumenina, 2013). The spectral resolution of EO-1/Hyperion in the VNIR part of the spectrum is 10 nm, which provides to derive information about the position of the red edge and narrow-band VIs. QUick Atmospheric Correction (QUAC) algorithm was applied on the selected channels in the respective spectral range using the module QUAC in ENVI (Bernstein, Adler-Golden *et al*. 2005; ENVI Atmospheric Correction Module User's Guide, 2010).

2.2. Data processing and analysis

2.2.1. Aggregate pollution index Z_c

Forest maps from the regional forestry services of the town of *Novi Iskar* were used in order to establish the heavy metal, metalloids, and radionuclide pollution in the examined region (Filchev and Yordanova, 2011; Filchev and Roumenina, 2012; Filchev and Roumenina, 2013). In order to determine the test sites a stratified random sampling was made within European black pine forests (McCoy, 2005). This sampling resulted in the 15 randomly distributed test sites (Filchev and Yordanova, 2011; Filchev and Roumenina, 2013).

According to the developed model it is envisaged to perform a GIS analysis by integrating the results from the processing of the satellite images at test site level. The test sites are sized 30 m × 30 m, i.e. the same size as is the spatial resolution of 1 pixel from EO-1/Hyperion. The test sites were chosen within landscape units characterized with the exact composition of natural and semi-natural environmental features. Some biometric parameters of coniferous trees, such as: tree density, age, and height (derived from forestry maps) were chosen to be homogeneous within the landscape units in order to eliminate the bias in collecting the spectra from EO-1/Hyperion image. This provides for a selection of 4 out of 15 test sites for analysis. Furthermore, the four test sites were grouped in two pairs appeared to be more contrasting in terms of aggregate pollution index - Z_c values, and hence under different stress conditions. This provides for the statistical representation of the integral assessment, as well as for the required spatial level of detail for analysis by additional ground-based data of the technogenic load of the examined region (*Fig. 1*).

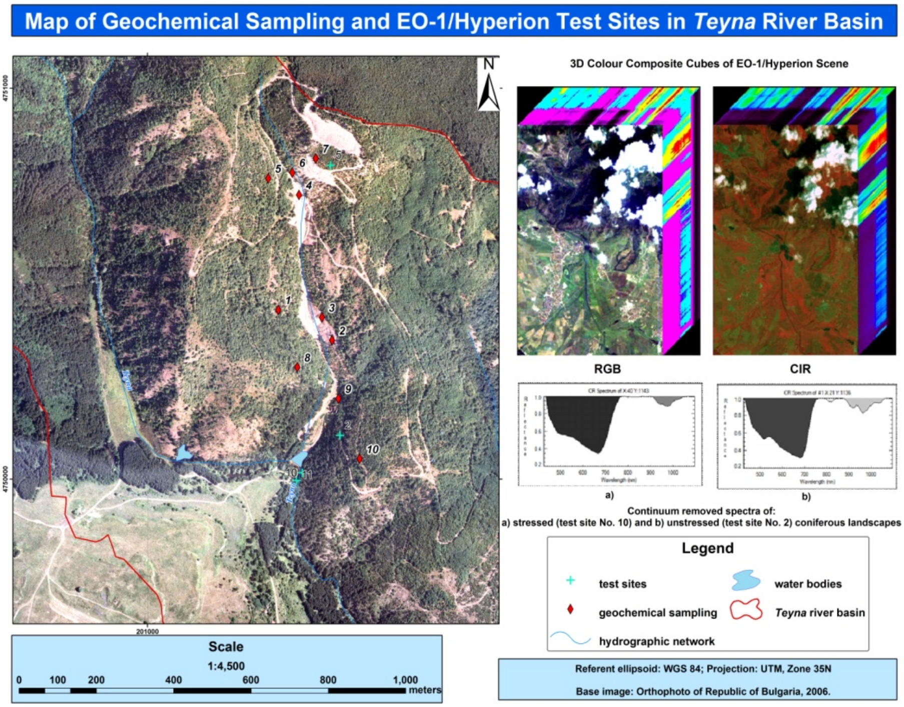


Fig. 1. Map of ground truthing and EO-1/Hyperion test sites in Teyna river basin

The assessment of the technogeochemical state of the examined coniferous landscapes for 1996 was made using the aggregate pollution index (Z_c), see equation 1, with respect to the background concentrations (Saet, Revich, Yanin, 1990; Vodyanitskii, 2010):

$$(1) \qquad Z_c = \sum_{i=1}^{n} K_c - (n-1) \quad .$$

where K_c is the technogenic concentration coefficient with $K_c>1$ (or 1.5), representing the ratio of heavy metal and metalloids concentrations and/or the specific activities of natural radionuclides in the topsoil (0-20 cm) to the background concentrations and specific activities determined for the examined region (Filchev and Yordanova, 2011; Filchev and Roumenina 2012; Filchev and Roumenina 2013):

$$(2) \qquad K_c = \frac{C}{C_{background}} \quad .$$

The distribution fields of Z_c were made using Geostatistical Analyst Extension in ArcInfo/ArcGIS 9.2 (Academic license). The interpolation method used for calculating the K_c and Z_c was the Inverse Multiquadratic Function (IMF) from the set of the Radial Basis Functions (RBF), since the Root Mean Square Error (RMSE) has found to be the lowest compared to other interpolation methods during cross-validation of the resulting layers (Filchev and Yordanova, 2011; Filchev and Roumenina, 2013).

2.2.2. Red-edge position

For present study the red-edge position, depth, asymmetry and area were calculated after the linear red-edge reflectance model (Guyot, Baret, Major, 1988):

$$(3) \qquad R_{red-edge} = \frac{(\rho_{670} - \rho_{780})}{2} \quad .$$

The position of the red-edge wavelength of the electromagnetic spectrum is given by (Van der Meer and De Jong, 2001):

$$(4) \qquad \lambda_{red-edge} = 700 + 40\left(\frac{(\rho_{red-edge} - \rho_{700})}{(\rho_{740} - \rho_{700})}\right) \quad .$$

2.2.3. Vegetation indices

The estimated and used four Vegetation Indices (VIs) in present study have exhibited higher correlation with the Z_c than the rest of the 30 VIs tested initially. Those VIs have proven to be good estimates of pigment content of the coniferous vegetation based on correlation between grounds measured chlorophyll and carotene as well as field spectrometry of the coniferous needles (Filchev and Roumenina, 2013). They are namely: Modified Chlorophyll Absorption in Reflectance Index (MCARI), Transformed CARI (TCARI), Modified Triangular Vegetation Index 2 (MTVI 2), Photochemical Reflectance Index 1 (PRI 1), (*Table 1*).

Table 1: EO-1/Hyperion VIs used for detection and assessment of the abiotic vegetation stress in coniferous landscapes

VIs	Equation	Source
MCARI	$MCARI= [(R_{700}–R_{670}) –0.2*(R_{700}–R_{550})]* (R_{700}/R_{670})$	(Daughtry *et al*, 1989)
TCARI	$TCARI=3*[((R_{700}−R_{670})−0.2*(R_{700}−R_{550}))* (R_{700}/R_{670})]$	(Haboudane *et al*, 2002)
MTVI2		(Haboudane *et al*, 2004)
PRI 1	$PRI1=(R_{528}-R_{567})/(R_{528}+R_{567})$	(Gamon *et al*, 1992)

2.2.4. Statistical analysis

Pearson correlation (r) and regression (r^2) analyses between the EO-1/Hyperion VIs and Z_c values were carried out. A set of dendrograms (cluster analysis) were prepared according to the hierarchical clustering (Ward method) using the derived VIs from EO-1/Hyperion satellite data and Z_c.

2.2.5. Validation

To assess the accuracy of geostatistical models, cross validation procedure was used. For this purpose the models were assessed by leaving out of the model a small subset of data from the sample. The accuracy of the models was assessed by the Root Mean Square Error of estimate (RMSE).

3. Results and Discussions

3.1. Red-Edge Position and Depth from EO-1/Hyperion Data

The spectra, extracted from EO-1/Hyperion satellite data, shows a blue shift of the red edge. The EO-1/Hyperion bands complying with the calculated position of the red-edge are band No. 32 with central wavelength of λ=671.02 nm, and band No. 33 at λ=681.20 nm. Difference is also registered in the depth, area, and asymmetry between the two isolated groups of plants: stressed and unstressed (Table 4). However, the highest difference is exhibited at test site No. 2, which red-edge position; depth, area, and asymmetry are completely different from the others. This can be explained with the fact that test site No. 2 is positioned on the left slope above the sludge pan. Hence, the geochemical leeching of the heavy metals and natural radionuclide is impossible. In this sense the test site No. 2 environmental conditions also can be assessed as closer to the background conditions than the rest of the test sites under investigation. This conclusion is supported also by the more recent investigation of the authors using field spectrometry measurements (Filchev and Roumenina, 2013). Conversely, the initially designated as most polluted test sites, i.e. test site 10 and 11, proved to be with close values of the red-edge position, depth, area and asymmetry. This similarity is supported not only by the background geochemistry but also by the relative closeness of the two test sites which are located tens to hundred meters down the stream after the technological sludge pan of *Teyna* River. The difference in the red-edge position between the test site No. 2 and test sites No. 10 and 11 is about 10 nm, which is within the bandwidth of available to the scientific community satellite hyperspectral systems such as EO-1/Hyperion and CHRIS/PROBA. Therefore, the detection capabilities of current satellite hyperspectral systems are very weak and need either higher spectral sampling rate at these zones of the spectrum or to look at different spectral derivatives for detection of chemical abiotic stress. Those distinctive features are obviously the depth, area and asymmetry of the red-edge feature which is not strictly bind to the limitations of spectral resolution of present satellite hyperspectral missions, (*Table 2*).

Table 2: Depth and position of the red-edge in the visible (VIS) part of the electromagnetic spectrum for EO-1/Hyperion data

Test site No.	Red-edge position λ (nm)	Depth	Area	Asymmetry
2	683.00	0.20	41.44	4.66
5	660.85	0.60	135.14	2.28
10	671.02	0.65	141.97	2.77
11	671.02	0.54	117.43	2.86

3.2. Statistical analysis

3.2.1. Correlation and regression analysis

The next step of the analysis is to perform a correlation between the grounds measured geochemical background expressed in modelled Z_c values and the VIs extracted from EO-1/Hyperion scene. It was found strong negative relationships between Z_c and TCARI and MCARI, and poor direct relationship between Z_c and PRI, (*Table 3*). The correlation between Z_c and the VIs proved the initial hypothesis that VIs were affected by the background geochemistry. However, the high inverse correlation between MCARI and TCARI is also reported between pigment content (chlorophyll) and the VIs (Haboudane *et al*, 2002). Therefore, at the rates of geochemical pollution the higher the pollution is the higher is the chlorophyll content is registered in the studied test sites. This conclusion is supported by a recent work of the authors which uses field spectrometry and ground-based biogeochemical data (Filchev and Roumenina, 2013). It is to be noted that the VIs such as TCARI and MCARI are less sensitive to heavy metal pollution than to natural radionuclide pollution (*Table 5*). Contrarily, the MTVI 2 and PRI exhibit stronger relationships with heavy metals (metalloids) than with natural radionuclide. However, even they are more sensitive to the metalloids concentration in soils their correlation coefficient is not higher enough in order to use them to make geochemical predictions. The strongest positive correlation is for TCARI/MCARI and Z_c ($r^2=0.63$; F: 5.20 at F: <0.1). The lowest correlation is between MTVI 2 and Z_c ($r^2=0.42$; F: 2.48 at F: <0.21), and accordingly between PRI and Z_c ($r^2=0.30$; F: 1.34 at F: <0.33).

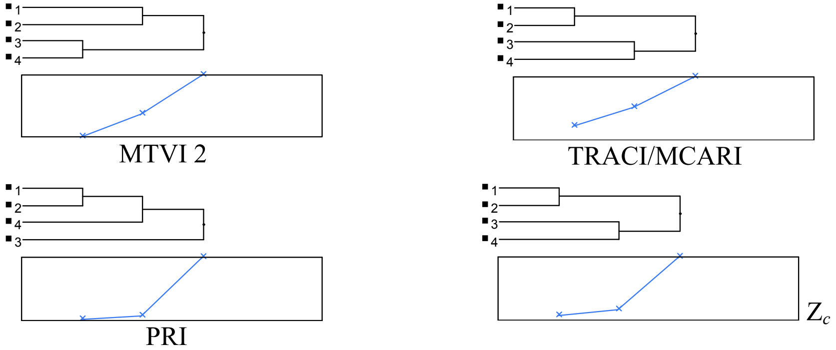
Table 3: Pearson correlation coefficient (r; α=0.05) for Z_c and EO-1/Hyperion VIs.

Variable	Z_c	Z_c radionuclide	Z_c metalloids
TCARI	-0.80	-0.80	-0.71
MCARI	-0.80	-0.80	-0.71
MTVI 2	-0.67	-0.66	-0.73
PRI	0.56	0.52	0.74

3.2.2. Cluster analysis

The areas subject to technogenic geochemical pollution were delineated based on the Z_c. Coniferous landscapes subject to abiotic stress were reclassified into four classes according to the values of the Z_c: unstressed (Z_c=0÷10), moderately stressed (Z_c=10÷20), stressed (Z_c=20÷50), and heavily stressed (Z_c>50) (Filchev and Roumenina, 2013). Within those areas only the test sites No. 2 and No. 5 (unstressed) and test sites No. 10 and No. 11 (stressed) were used in the cluster analysis in order to test whether the Z_c values group similarly to the VI_s values from EO-1/Hyperion. The results are represented on (*Figure 2*).

Fig. 2: Dendrograms of clustering of EO-1/Hyperion VIs and Z_c. The numbers on the figures correspond to: 1- test site No. 2; 2 – test site No. 5; 3 – test site No. 10; 4 – test site No. 11



On Fig. 2, MTVI 2 and TCARI/MCARI values group their first cluster relatively farther than Z_c. However, the PRI does not reflect the Z_c clusters. These results also support the conclusions for the VI's performances for abiotic stress detection drawn from visual comparison between dendrogrammes from field spectrometry data, although there only the first Principal Component of the VIs and field pigment data correspond to the Z_c groupings (Filchev and Roumenina, 2013).

4. Conclusions

Through the joint use of satellite spectrometry data and VIs from EO-1/Hyperion and ground-based geochemical data, it was established that coniferous forests are subject to abiotic stress caused by uranium mining. It was found that, in sattelite spectra, the position of the red-edge with stressed trees is shifted slightly towards the orange and green part of the spectrum, i.e. the so called “blue shift”. With healthy plants this shift is at λ=683 nm, while it is at about λ=671 nm for the stressed ones. Furthermore, the stressed coniferous plants feature a non-specific stress reaction or „exstress” or an increased chlorophyll and carotene content with increased levels of geochemical pollution - Z_c. It should be noted however, that the registered effects from geochemical pollution are specific to at a certain point after which the saturated geochemical background has an adverse impact on the vegetation expressed in chlorosis (yellowing) and die out of the coniferous trees.

It has also been found out that the VIs such as TCARI/MCARI and Z_c (r^2=0.63; F: 5.20 at F: <0.1) has the highest correlation followed by MTVI 2 and Z_c (r^2=0.42; F: 2.48 at F: <0.21), and PRI and Z_c (r^2=0.30; F: 1.34 at F: <0.33). Therefore, the space borne derived VIs from hyperspectral sensors at present level of technology development may be used as an indirect indicator neither of geochemical background stress nor for stress detection caused by uranium mining in coniferous landscapes due to the weak relationships between geochemical background and narrowband vegetation indices. However, the correlation between the four obtained VIs and Z_c led to the conclusion that most VIs, using chlorophyll absorption lines, shows a very strong inverse correlation relationship with the Z_c.

In conclusion, the study will continue with an investigation of the narrowband VIs which feature the most distinctive relationship between VIs and the modelled Z_c values. Those studies will benefit from employing rigorous and versatile models for pollutant distribution in soils and reclaimed lands.

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ОТКРИВАНЕ И ОЦЕНКА НА АБИОТИЧЕН СТРЕС, ПРИЧИНЕН ОТ УРАНОДОБИВ, В ИГЛОЛИСТНИ ЛАНДШАФТИ (С ИЗПОЛЗВАНЕ НА СПЪТНИКОВИ СПЕКТРОМЕТРИЧНИ ДАННИ ОТ ЕО-1/HYPERION)

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Резюме

В статията са представени резултатите от проведено изследване с цел откриване и оценка на абиотичен стрес в иглолистни ландшафти на черноборови монокултури (Pinus nigra L.) с помощта на геохимични наземни данни, модели на техногенно замърсяване, както и спътникови спектрометрични изображения от ЕО-1/Hyperion. Изследвани са вегетационните индекси (ВИ): MCARI, TCARI, MTVI 2, и PRI, както и атрибутите на червения ръб, с цел откриване на промени, причинени от геохимично замърсяване вследствие на уранодобив. Анализът е извършен на четири тестови участъка с размери всеки 30 m × 30 m, съответстващи на размера на подпикселното пространство на ЕО-1/Hyperion, заложени в хомогенни иглолистни ландшафти в

басейна на р. Тейна - ляв приток на река Искър. В резултат е установена позицията на червения ръб за нестресирани иглолистни ландшафти (черен бор) λ=683 nm, както и за стресирани иглолистни ландшафти λ=671 nm. Установено е, че вегетационните индекси, като TCARI / MCARI и сумарния коефициент на техногеохимично замърсяване - Z_c са силно корелирани (r^2=0.63; F: 5.20 на F:<0.1), последвани от MTVI 2 и Z_c (r^2=0.42; F: 2.48 на F:<0.21), и PRI и Z_c (r^2=0.30; F: 1.34 на F:<0.33). Тествана е хипотезата, че групирането на EO-1/Hyperion ВИ съответства на клъстеризацията на Z_c стойностите използвайки метода на йерархичната клъстеризация (по метода на Ward). За тази цел, избраните четири тестови участъка са разделени на две двойки съответстващи на моделните стойности на Z_c (използвайки инверсна мултиквадратна функция - IMF от множеството на радиално базираните функции - RBF): 1) нестресирани (тестови участъци № 2 и № 5) и 2) стресирани иглолистни ландшафти (тестови участъци № 10 и № 11). В резултат на това е установено, че групирането на стойностите на MTVI 2 и TCARI/MCARI на първия клъстер става сравнително по-далече от първия клъстер на Z_c. Съответно клъстеризацията на PRI не отразява клъстерите Z_c. Това води до заключението, че спътниковите спектрометрични тесноканални ВИ получени от EO-1/Hyperion, не са достатъчно чувствителни, към геохимичния фон и абиотичния стрес на иглолистните ландшафти, причинен от геохимичните замърсявания от уранодобива.