

## RELATING PLANT GROWTH AND SPECTRAL RESPONSE TO ECOLOGICAL FACTORS

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**ABSTRACT.** Remote sensing is recognized as a powerful tool in numerous scientific and application fields. Remote sensing surveys have become an operational technology in managing problems of global importance, such as accelerating environmental changes and ecosystems degradation. The derived information supports solutions for more rational and sustainable land-use, biodiversity conservation and natural resources preservation. Recent developments in environmental studies are greatly related to ecological problems arising from increasing anthropogenic impacts on the biosphere and especially on vegetation. The interrelated nature of many environmental issues imposes the necessity to conduct interdisciplinary research and implement different approaches as well as to share and integrate the acquired data. Remote sensing provides advanced monitoring and alerting techniques, timely information extraction, modeling and forecasting possibilities used for decision-making in environmental control policies. In this paper we report results from an experimental study designed to make use of vegetation spectral features in assessing plant performance under different growth conditions. We investigate and analyze the relationship between growth variables and spectral response of agricultural species to abiotic stress factors (heavy metal pollution, nutrient deficiency and soil acidity). Multispectral data obtained from ground-based optical spectroradiometric measurements are examined in terms of the relation to ecological factors and the ability to serve as an indicator of crop performance.

### ВРЪЗКА НА РАЗВИТИЕТО И СПЕКТРАЛНИТЕ ХАРАКТЕРИСТИКИ НА РАСТИТЕЛНОСТ С ЕКОЛОГИЧНИТЕ УСЛОВИЯ

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**РЕЗЮМЕ.** Дистанционните изследвания са признати като информативно средство в множество научни и приложни области. Изследванията чрез дистанционни наблюдения са станали оперативна технологии в управлението на проблеми от глобално значение, като например ускоряването на промените в околната среда и деградацията на екосистемите. Извлечената информация подпомага вземането на решения за по-рационалното и устойчиво земеползване, за опазването на биологичното разнообразие и на природните ресурси. Новите постижения в изучаването на околната среда са силно свързани с екологични проблеми, произтичащи от увеличаването на антропогенните въздействия върху биосферата и особено върху растителността. Взаимосвързаният характер на много от проблемите на околната среда налага необходимостта да се провеждат интердисциплинарни изследвания и да се прилагат различни подходи, както и да споделят и да се интегрират придобитите данни. Дистанционните изследвания предлагат множество възможности като мониторинг и сигнализиране в реално време, навременно извличане на информация, моделиране и прогнозиране, използвани за вземане на решения по политиките за контрол на околната среда. В тази работа представяме резултати от експериментално изследване, имащо за цел да се използват спектралните характеристики на растителността при оценка на състоянието на посевите при различни условия на растеж. Ние изследваме и анализираме връзката на растежните променливи и регистрираната промяна в спектралните характеристики на земеделските култури с абиотични стресови фактори (замърсяване с тежки метали, дефицит на хранителни вещества и киселинност на почвата). Многоспектралните данни, които са получени по време на наземни оптични спектрометрични измервания, се разглеждат от гледна точка на връзката им с екологичните фактори и на способността им да служат като показател за продуктивността на селскостопанската растителност.

### Introduction

The expansion of industrial development and rapid urbanization pose serious ecological problems associated with the increasing anthropogenic pressure on the environment. Destructive processes caused by human activities are in the focus of the scientific research and occupy the attention of social communities and government authorities. Air, water and soil pollution and its negative effects on the biosphere with unfavourable short-term and long-term consequences are a worldwide ecological problem. Industry, agriculture, forestry, and transportation all generate substances and by-products that are considered pollutants and contribute a significant impact on the environmental quality. Contaminated environments are a continuing concern because of the potential risks to natural resources and human health.

Ecological monitoring and control are an objective of a great variety of projects, multipurpose programs and interdisciplinary research. In agriculture, abiotic stressors, including different types of pollution, are the most harmful factors concerning species growth and productivity. Heavy metals are among the most dangerous pollutants because of their high toxicity to organisms, persistent nature, high mobility, and long biological half-life. They constitute a group of environmentally hazardous substances whose deposition in soils and easy uptake by species affect soil fertility, plant development and production. In recent time, the desire for food safety and security has stimulated research on the danger associated with the consumption of food contaminated with heavy metals and other toxins. Soil is the primary recipient of these contaminants. Plants take up and absorb them and then they enter the food chain. Plant damage associated with heavy metals is of great concern throughout the world because of

their toxic and mutagenic effects even at low concentration. Therefore, particularly great interest has focused on heavy metal-induced stress in plants, its mechanisms of action, consequences, and prevention (Rodriguez-Serrano et al., 2009; Bavi et al., 2011; Sobukola et al., 2010; Abii, 2012).

The interrelated nature of environmental problems has imposed the need of data integration and information sharing between different databases. Advanced monitoring, risk detection and early warning techniques, timely information retrieval, modeling and forecasting possibilities are prepositions for successful data application and decision support in developing policies and strategies dealing with environmental issues. In this respect, remote sensing is an essential tool in ecology-related research. It plays an expanding role in vegetation studies and especially for diagnosis of plant stresses. In agriculture, a primary goal of remote sensing is the assessment of crop development throughout the growing season. Agricultural lands are subjected to enormous pressure and their monitoring and assessment have become an important economic and ecological issue. The spreading acceptance of the concept of precision agriculture running generates much interest in the early detection of crop stress. The implementation of modern remote sensing technologies is one of the basic assumptions of this concept (Seelan et al., 2003; Liaghat and Balasundram, 2010). A lot of attention has been devoted to studying the influence of unfavourable environmental conditions on species performance and the relationship with their spectral behaviour. The impact of stress factors, such as drought, nutrient deficiency and toxic pollution, is described and evaluated from plant spectral response data. Various multispectral features have proven capabilities for crop health assessment and detection of stress situations (Carter et al., 1996; Penuelas et al., 1994; Serrano et al., 2000; Filella et al., 2004; Kancheva et al., 2005; Kancheva and Borisova, 2007; Baret et al., 2007; Franke and Menz, 2007; Falkenberg et al., 2007).

The interactions between vegetation canopies and incident radiation lie at the root of vegetation remote sensing. Remote sensing of vegetation is based on the analysis of plant reflectance and emittance properties as a function of plant physiology and morphology. Vegetation spectral behaviour depends on plant biophysical and biochemical variables and reveals significant sensitivity to them. Growth variables are defined by plant development processes and health condition. This means that variations of plant performance cause spectral response changes. On the other hand, vegetation health and vigour are an expression of the growing conditions (meteorological, soil properties, agricultural practices) including stress factors (nutrient deficiency, high temperatures, drought, contamination, etc.). As such, knowledge of plant spectral response to different environments is necessary to interpret remote sensing data and extract the information content of spectral data. The information is carried by the specifics of vegetation spectral characteristics which depend on biomass amount, leaf area, canopy cover, chlorophyll content, and etc. The relation "growing conditions - plant state - spectral features" determines the informational potential of multispectral data and provides grounds for vegetation stress detection.

In view of all this, our paper studies various features of plant spectral response to crop performance and growing conditions.

We use multispectral data in the visible and near infrared wavelength range to and describe plant canopies. Growth variables are associated with the phenological development and related to crop state and growing conditions. Spectral variables are used to characterize crop performance under different conditions. The paper is devoted particularly to studying the impact of heavy metal contamination and the role of the soil type and nitrogen fertilization on agricultural species. The main goal is to examine the ability of spectral signatures to serve as sustainable stress indicators. Stress factors and their effects on crop performance (growth and productivity) are related to plant spectral response in a statistical manner. The derived empirical relationships allow not only stress detection from plant spectral data but also stress monitoring during plant development period and quantitative assessment of stress-induced growth changes.

## Materials and Methods

The paper presents some results of an extended study on the impact of stresses on crop performance and spectral behaviour. The research comprised greenhouse and laboratory experiments. Spring barley, peas and alfalfa were cultivated under different conditions and controlled combinations of factors. The pot trials included spring barley grown on neutral (pH=7.0-7.5) chernozem soil and acid (pH=5.0-5.5) grey forest soil. These soils were chosen for their different properties and response to heavy metal pollution. The soils were contaminated with Ni in concentrations 0 (control), 100, 200, 300 and 400 mg/kg. In addition, different nitrogen fertilizers were applied to treatments with equal 200 mg/kg Ni concentrations. Calcium nitrate  $\text{Ca}(\text{NO}_3)_2$ , ammonium nitrate  $\text{NH}_4\text{NO}_3$  and potassium nitrate  $\text{KNO}_3$  were used in amounts to provide equal N supply. The effects and interactions of the three factors: Ni, soil pH and N-form, were examined as conditions influencing crop performance. The trials were grown from seeding to harvest. Peas and alfalfa were grown in greenhouse conditions on the same soil types. The stress factor applied was Cd-contamination of the soil in concentrations 0, 5, 10, 20 and 30 mg/kg. The experimental design included also spring barley fertilization treatments with varying nitrogen supply rates (0, 200, 400, 600, 800 and 1000 mg/kg) of ammonium sulphate  $(\text{NH}_4)_2\text{SO}_4$ . The greenhouse trials were conducted in 3-5 replications. A second set of experiments comprised peas hydroponically grown in different media (water and green algae supernatant) and subjected to Cd contamination in concentrations 0, 5, 10, 20 and 30 mg/l. The heavy metal was introduced through  $\text{CdCl}_2 \cdot 2.5\text{H}_2\text{O}$ . These treatments were replicated twice. The variety of growing conditions and their interactive effects ensured a wide range of plant performance and physiological status thus causing considerable variations of the spectral behaviour of the trials.

Reflectance, biometric and phenological data were collected on the greenhouse treatments throughout the entire growing season from emergence to full maturity for barley and to second harvest for alfalfa plots. Visible (VIS) and near infrared (NIR) multispectral measurements were carried out in the wavelength range 400-820 nm. Reflectance measurements were conducted at canopy level at weekly intervals. Crop performance under varying conditions was characterized by key growth variables (biomass, canopy cover fraction, height, pigment content) and yield (alfalfa biomass after harvest and

barley grain production). The datasets were statistically analyzed to assess and describe the variations in plant development as a function of environmental conditions (heavy metal contamination, soil properties and nutrient deficiency). Multispectral reflectance data acquired during plant development were linked to plant variables and stress factors and examined for the ability to detect and quantify stress-induced changes in plants. Plant spectral response was examined for its sensitivity to crop performance (growth variables and productivity) and the stress level. Analysis of variance was conducted to determine the statistical significance of the differences between the samples (between replications and between different treatments). The analysis of variance allowed also to reveal the individual and interactive effects of the applied factors. Correlation analysis of the datasets was performed in order to determine the presence and strength of the relation between plant spectral and biophysical characteristics as well as to reveal the dependence of these variables on the growing conditions. Through regression analysis conducted on phenology-specific basis, i.e. at different phenological stages, empirical relationships were derived describing plant spectral and physiological response to the applied factors. Spectral models of plant performance were established quantifying the stress impact.

Remote sensing techniques make use of multispectral data to estimate plant biophysical and biochemical characteristics which are factors effecting plant canopy reflectance. Spectral variations carry information about plant growth and health condition, and the goal of data analysis is to extract this information. A common technique for multispectral data processing is the use of spectral transforms called vegetation indices (VIs). They are calculated as various combinations (Carter et al., 1996; Penuelas et al., 1994; Broge and Leblanc, 2000; Kancheva and Borisova, 2007; Glenn et al., 2008; Hatfield and Prueger, 2010; Osório et al., 2012) of the measured spectral reflectance factors  $r_\lambda$  and are defined usually as different ratios at two or more wavelengths or normalized differences. The wavelengths correspond to specific absorption and high reflectance regions of vegetation spectrum in the green (G - 550 nm), red (R - 670 nm) and near infrared (NIR - 800 nm) range, or are located within the R-NIR interval (680-780 nm) where the reflection increases steeply. Various spectral indicators were used in our study to characterize crop performance under different conditions.

## Results and Discussion

In our study we examined a big number of vegetation indices for their correlation with plant variables and the applied stress factors. Various ratio combinations in different reflectance bands were calculated from the acquired multispectral data. Regression analysis was run on those indices which showed the best correlation with plant growth attributes and stress factors, the obtained empirical regressions being significant at 95% level of confidence. Special attention was paid to temporal aspects of plant spectral properties throughout the growing period. Statistical relationships were established also between the stress level and plant spectral and biophysical response, thus attaching a quantitative measure to the stress impact on crops. A comparison was made of the evaluated stress degree from growth and spectral data. The comparison

demonstrated a very good agreement between the estimates from stress bioindicators (reduced canopy cover fraction and biomass, lower yield) and from spectral indicators (vegetation indices)

In this section we illustrate the performance of some vegetation indices for assessing plant condition and detecting nutrient and heavy metal-induced stress. Significant variations of crop biological and spectral performance were observed associated with the heavy metal impact. These variations were more pronounced and statistically meaningful for the trials on grey forest soil.

In the heavy metal treatments, significant worsening of plant performance was observed, especially of the trials on grey forest soil. Stress induced by heavy metals manifested itself in plant growth depression and resulted in reduced biophysical parameters. Ni and Cd inhibited also chlorophyll synthesis and accelerated carotenoid cumulation. Stress-induced changes of growth variables affected in turn plant reflectance features and a consequence of plant depression were variations of canopy spectral response. Strong correlations were found between spectral indicators and plant attributes. In Table 1 the correlation coefficients of different vegetation indices with peas growth variables and Cd concentration are given.

Table 1.  
Correlation coefficients between vegetation indices and growth variables of Cd-polluted pea plants

VI	Height	Biomass	Cover	Cd
$(r_{820} - r_{670}) / (r_{820} + r_{670})$	0.88	0.86	0.97	-0.97
$r_{820} / r_{670}$	0.93	0.92	0.99	-0.97
$(r_{820} - r_{550}) / (r_{820} + r_{550})$	0.75	0.75	0.93	-0.96
$r_{820} / r_{550}$	0.77	0.76	0.94	-0.97
$(r_{550} - r_{670}) / (r_{550} + r_{670})$	0.96	0.96	0.97	-0.93
$r_{550} / r_{670}$	0.97	0.98	0.96	-0.91
$r_{820} \cdot (r_{550} - r_{670}) / (r_{550} + r_{670})$	0.89	0.90	0.98	-0.95
$r_{670} / (r_{550} - r_{670})$	-0.90	-0.90	-0.96	0.94
$r_{670} / (r_{550} + r_{820})$	-0.86	-0.86	-0.97	0.97
$r_{550} / (r_{670} + r_{820})$	-0.71	-0.71	-0.91	0.95
$(r_{670} \cdot r_{670}) / (r_{620} \cdot r_{720})$	-0.90	-0.89	-0.98	0.97
$\sqrt{(r_{550} \cdot r_{550}) + (r_{820} \cdot r_{820})}$	0.50	0.50	0.75	-0.77

One more evidence of the high correlation between spectral indices and stress factors is Table 2 which presents the established coefficients of correlation between various VIs and Cd concentration in the grey forest soil for alfalfa at different phenology stages. As it can be seen, the stress effect became stronger with time (and higher the correlation) which is explained with the longer action of the heavy metal.

The contamination impact on crop growth variables and reflectance features was quantitatively described by regression analysis. Notable differences in vegetation reflectance, especially in the infrared portion of the spectrum, were attributed to green canopy fraction. This growth variable is a factor of vegetation spectral reflectance and, on the other hand, is closely related to other plant characteristics such as (biomass, leaf area index, density, etc.) being indicative of crop development. Canopy reflectance signatures considerably varied with the amount of soil exposed, i.e. with canopy fraction.

Table 2.  
Correlation coefficients between Cd concentration in the grey forest soil and vegetation indices of alfalfa at different phenological stages: real leaf (1), rosette (2), button forming (3), and before flowering (4)

VI	1	2	3	4
$(r_{800}-r_{670})/(r_{800}+r_{670})$	-0.69	-0.74	-0.83	-0.91
$(r_{550}-r_{670})/(r_{550}+r_{670})$	-0.67	-0.79	-0.83	-0.9
$r_{710}/r_{670}$	-0.69	-0.74	-0.81	-0.88
$(r_{800}-r_{670})/r_{800}$	-0.68	-0.73	-0.83	-0.89
$(r_{550}-r_{670})/r_{550}$	-0.68	-0.79	-0.84	-0.89
$(r_{720}-r_{700})/r_{720}$	-0.81	-0.78	-0.85	-0.92
$(r_{720}-r_{670})/r_{720}$	-0.74	-0.79	-0.81	-0.87
$r_{670}/(r_{800}+r_{550})$	0.71	0.75	0.84	0.9
$r_{550}/(r_{650}+r_{670})$	-0.68	0.77	0.83	-0.91
$r_{670}/(r_{800}+r_{670}+r_{550})$	0.71	0.75	0.84	0.91
$r_{800}/(r_{670}+r_{680}+r_{690}+r_{700}+r_{710}+r_{720})$	-0.67	-0.79	-0.85	-0.9
$\sqrt{(r_{800}-r_{670})/(r_{800}+r_{670})+0.5}$	-0.68	-0.78	-0.83	-0.9

Seasonal changes are a distinguishing feature of species biophysical and spectral properties. In agricultural monitoring, remote sensing time series data are a source of valuable information about the growth process. This determines the importance of studying the relationships between crop variables and spectral response at different stages of plant development. The temporal behavior of spectral indices represents a typical canopy expansion and senescence curve and proves useful for crop growth assessment by tracking the onset and duration of phenological events. Crop stress detection from multitemporal data is based on the temporal trends and characteristics of vegetation index temporal curves (amplitude, minimum and maximum values, integrated area under the curve, slopes, and so on). The impact of Ni contamination on the seasonal behaviour of the (NIR-R)/(NIR+R) index of spring barley on grey soil is shown in Figure 1a. In Figure 1b the link between Ni contamination level and spectral data acquired during the growing season is shown.

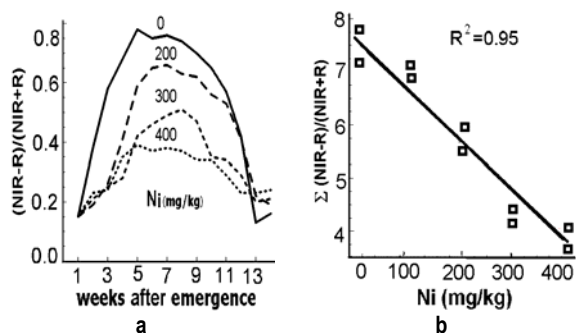


Fig. 1. Dependence of the temporal behavior of barley (NIR-R)/(NIR+R) spectral index (a), and accumulated sum of the index during the growing season (b) on Ni concentration in the grey forest soil

The temporal profiles considerably differed during the vegetative period. They denoted differences of crop performance and detected differences of plant condition related to the occurrence of stress. Temporal spectral patterns were indicative not only of plant depression but also of the stress level. The important point is that stresses were observed throughout the whole growing season and could be already detected at early stages of the phenological development.

Seasonally-integrated sums  $\Sigma VI_t$  of various vegetation indices were associated with crop stress response and related to yield. In Figure 2 an example of yield prediction applying this model is shown. Using the temporal sum of the spectral index and the obtained regression equation, the grain yield from three barley treatments was estimated. The nitrogen fertilizer type effected plant spectral behaviour, while the other factors (soil type, contamination, nitrogen amount) were constant. Good correspondence was found between actual (measured) and modeled (estimated) yield values, the maximum relative error being about 12%. Yield prediction models with high accuracy were developed also for half-season VI sums and VI values at single growth stages. Temporal spectroradiometric data distinctly tracked plant ontogenetic changes and were able at the same time to discriminate between plant health conditions. This explained the fact that accumulated VIs values during growth were found to be very closely related to crop yield. An advantage of using multitemporal predictions is that they account for any unfavorable effects on species development that exist or might occur during the growing season, and thus can serve as a type of "dynamic" predictors.

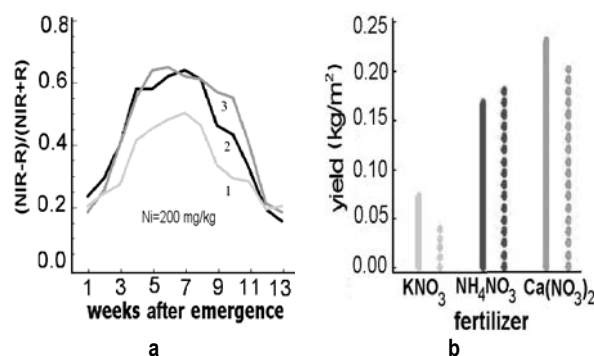


Fig. 2. Relationship between barley grain yield and (NIR-R)/(NIR+R) whole-season sum (a); actual (—) and predicted (---) from the regression model barley yield of equally Ni-contaminated (200 mg/kg) treatments with different fertilizers applied (b)

Soil properties were another factor effecting plant performance, especially in combination with other growing conditions. Neutral chernozem and acid grey forest soils exhibited different behaviour to heavy metals whose mobility and uptake by plants increased with higher soil acidity. The influence of the soil type was statistically significant and manifested in reduced heavy metal impact on crop growth in the case of chernozem soil trials and stronger stress impact on the acid soil treatments. There were not big yield differences between the control non-polluted treatments grown on both soils, the grain yield of the chernozem plots being about 10% higher. The polluted spring barley and alfalfa treatments grown on chernozem were less affected by the heavy metal than those on the grey forest soil. As a consequence, much smaller variations of plant spectral response to contamination of the chernozem soil were observed. This is clearly illustrated by Figure 3a and 3b. They show (NIR-R)/(NIR+R) seasonal profiles of control and equally Ni-polluted spring barley treatments grown respectively on chernozem and grey soil. On the contrary, considerable spectral variations were observed for treatments on grey forest soil in relation to Ni concentrations (see also Figure 1a). The acidity of the soil in this case increased the mobility and accessibility of heavy metals to plants thus stronger inhibiting their growth.

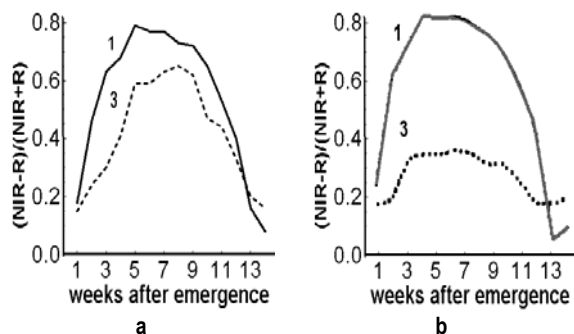


Fig. 3. (NIR-R)/(NIR+R) seasonal profiles of control (1) and 400 mg/kg Ni-polluted (3) spring barley treatments on neutral chernozem (a) and acid grey forest (b) soil

Nutrient supply was another factor detected by measurements of plant reflectance response. Figure 4a shows the impact of nitrogen concentration in leached chernozem soil on NIR/G temporal profiles of barley fertilization treatments. As evident from the plot, nutrient deficiency was clearly manifested and observed from multispectral data. Differences in crop reflectance were observed also in relation to the fertilizer form regardless of the equal nitrogen amount as illustrated in Figure 4b which presents the variance of NIR/G temporal behavior of barley trials with equal nitrogen concentration introduced through different fertilizers. Spectral reflectance was a reliable sign and measure of plant growth performance.

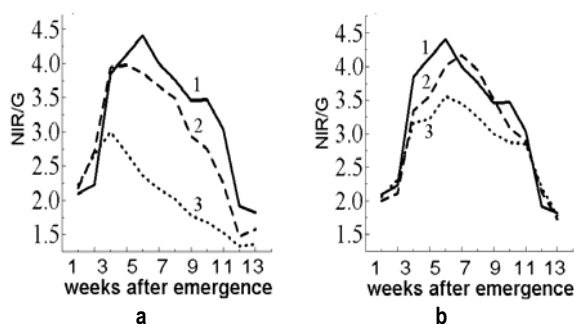


Fig. 4. Temporal behaviour of NIR/G spectral index of spring barley treatments with different nitrogen concentration: 1 - 800 mg/kg, 2 - 200 mg/kg, 3 - 0 mg/kg introduced through the same fertilizer  $(\text{NH}_4)_2\text{SO}_4$  (a); and with equal nitrogen concentration (800 mg/kg) introduced through different fertilizers (b): 1 -  $(\text{NH}_4)_2\text{SO}_4$ , 2 -  $\text{NH}_4\text{NO}_3$ , 3 -  $\text{KNO}_3$

## Conclusions

The obtained results indicate that growing conditions cause statistically significant variations of plant spectral response associated with the sensitivity of the reflectance properties to crop growth characteristics. Various spectral features (vegetation indices) are highly correlated with stress impacts resulting in our study from heavy metal contamination and nutrient deficiency. Multispectral and multitemporal data proves applicable for reliable diagnosis of plants and detection of stress symptoms. Growth depression expressed in variations of plant performance is successfully evaluated from spectral measurements. The derived empirical dependences of biophysical and spectral variables on factors effecting growth attach a quantitative measure to plant condition assessment. They permitted not only to discriminate between depressed and healthy canopies but also to quantitatively describe

negative impacts and assess the degree of stress. These findings highlight a promising strategy for applying remote sensing techniques and spectrally-based approaches to characterize dynamic and environmentally sensitive aspects of species physiological development.

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