# Spectral models for crop state assessment considering soil and anthropogenic impacts

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Aerospace information gathered by different sensors and Earth observation missions has become an undoubted necessity in various investigation and application fields. Remote sensing data address many world significant problems such as ecosystem change detection, natural resources management, environment preservation, etc. Vegetation monitoring is among the priorities of these investigations being the most important component of the biosphere. In agriculture remote sensing applications are associated with plant growth assessment, stress detection, yield forecasting. This paper is devoted to the relationships between agricultural vegetation spectral and biophysical features with consideration of some growth conditions. The influence of soil properties and anthropogenic factors (fertilization, heavy metal pollution) on crop spectral response has been examined in relation to the applicability of spectral models to estimate plant variables and assess crop state and stress impacts.

## INTRODUCTION

In the contemporary world aerospace information gathered by different sensors has become a necessity in various investigation and application fields. Vegetation monitoring is among the priorities of these investigations. In agriculture remote sensing is a tool that is used to assess plant development process and retrieve information about plant growth parameters for subsequent input into models for crop state assessment and yield forecasting. Ground-based studies are a reference source for verification of remotely sensed data. Especially advantageous is the ability to vary and control the experimental conditions getting a precise picture of plant spectral response to different factors as well as to track in detail temporal aspects of plant spectral properties during the ontogenetic process.

The retrieving of quantitative information using vegetation reflective and emissive spectra is the objective of numerous papers. Prevailing part of them deal with green phytomass estimation, plant growth evaluation and yield prediction [1-5]. Empirical modelling is one of the most widely spread technique for vegetation assessment [6-9]. Different conclusions have been made about the applicability of the obtained models because of their dependence on local conditions and site-to-site or year-to-year discrepancy [6, 10].

This paper is further dedicated to the spectral-biophysical modelling of agricultural vegetation considering the growth conditions. The goal is to examine the impact of soil properties and anthropogenic factors (nutrient supply and heavy metal pollution) on plant spectral behaviour in relation to crop state evaluation and stress assessment. Ground-based VIS and NIR spectral measurements have been carried out along with phenological and biometrical observations in order to establish empirical relationships between plant reflectance features, growth variables, productivity and applied treatments.

## MATERIALS AND METHODS

Reflectance, biometrical and phenological data were gathered from spring barley plots within a green-house experiment. The treatments comprised of two soil types (grey forest soil and chernozem soil), Ni pollution in different concentrations and different fertilization conditions. The spring barley was grown over neutral (pH=7.0-7.5) chernozem soil and acid (pH=5.0-5.5) grey forest soil. The soils were chosen for two reasons - their different reflectance spectra and different response to heavy metal pollution. Four Ni concentrations of 100, 200, 300 and

400 mg/kg and equal nutrient amount of $NH_4NO_3$ fertilizer were applied. In the case of 200 mg/kg Ni concentration two more treatments were added with $(NH_4)_2SO_4$ and $KNO_3$ fertilizers.

Reflectance data were acquired with a multichannel portable spectrometer from the nadir position over the wavelength range 0.4-0.8 μm at a 10 nm interval. Spectral measurements were performed weekly during plant development, from emergence till full maturity. Among the various growth and ecologically relevant variables that have been measured, the presented here results concern mainly plant canopy cover, above-ground biomass, leaf area index (LAI) and yield. The reason is that variations in vegetation reflectance are most attributed to green cover which is at the same time a primary indicator of crop state. Biomass amount and LAI are important physiological parameters related to plant development and yield forming processes.

The data sets were statistically analysed to determine correlations and derive empirical relationships between plant reflectance spectra, biophysical variables and applied treatments. A regression analysis was run on vegetation spectral indices using band ratios, contrasts and normalized differences as routinely implemented data transformations [11-13]. The selected wavelengths correspond to the specific absorption and high reflectance bands of vegetation spectra in the green (550 nm), red (670 nm) and near infrared (800 nm) range. Spectral indices were chosen from those having the best statistical correlation with plant bioparameters and applied factors, the obtained empirical regressions being significant at the 95% level of confidence. Special attention was paid to temporal aspects of plant spectral properties throughout the growing period. The temporal behaviour of vegetation indices was regarded as a function of plant ontogenesis and used as a crop diagnostic feature and yield predictor. Significant variations in plant state and spectral performance were observed associated with the impact of soil properties and anthropogenic factors.

## RESULTS AND DICUSSION

Various combinations of spectral ratios [14, 15] were examined for their correlation with plant bioparameters and the Ni contamination. Many of them demonstrated high $R^2$ values from 0.86 to 0.97. As the normalized difference of the measured spectral reflectance in the red and near infrared band is traditionally and most widely used, the presented below examples refer mainly to this spectral index. In Fig. 1 the statistical relationships of (NIR-R)/(NIR+R) and barley canopy cover are shown. The dependences were derived separately for the grey (1) and chernozem (2) soil plots.

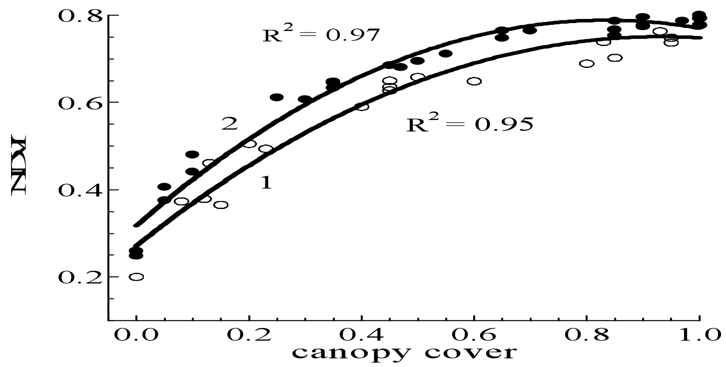



*Fig. 1. Dependence of the (NIR-R)/(NIR+R) spectral index on barley canopy cover for the treatments over grey (1) and chernozem (2) soil*

If a soil-non-accounting regression curve is used the estimation error increases almost twice, the canopy cover of the brighter grey soil treatments being systematically underestimated and overestimated for the dark chernozem soil treatments. Fig. 2 presents the spectral reflectance characteristics of the two soil types.

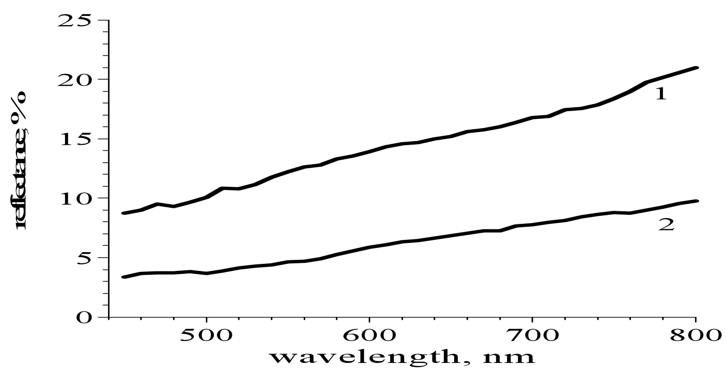



*Fig. 2. Spectral reflectance characteristics of grey forest soil (1) and chernozem soil (2)*

Statistically significant spectral models were developed also for plant biomass and leaf area index. It is quite explicable considering the high correlation obtained between plant variables ($R^2$=0.86-0.94).

Since plant variables (canopy cover, leaf area index, biomass) define the yield potential, they serve as crop growth and productivity indicators. Estimated from spectral data and compared to reference values (maximum or average statistics for given species and agrometeorological conditions), they can be used as crop "state indices" - SI. For instance, in our experiment the maximum measured LAI at pre-heading stage of barley unpolluted control plots was 5.0. For a grey soil treatment with ground-measured LAI of 2.47 the state index calculated in a ratio manner is $SI_{LAI}$=2.47/5=0.49 which means that crop state in this case is almost half worst of the best one in terms of LAI. Further, estimation of $SI_{LAI}$ from spectral data was performed in the following way. The measured NDVI of the same plot was 0.65. Calculating LAI from the established regression equation LAI = exp (−2.83+5.93*NDVI) ($R^2$=0.95) we obtained LAI=2.78, then $SI_{LAI}$=2.78/5=0.55. So the actual and spectrally-estimated state indices were close enough (differing with about 10-12%). Moreover, comparing the canopy cover of the plot (0.5) estimated from spectral data (NDVI=0.65) and the dependence in Fig.1 with the maximum observed (1.0) we obtain a state index in terms of the canopy cover $SI_{cover}$ =0.5/1.0=0.5 which is in a very good agreement with the LAI state index. This example and the results from more test data showed a good correspondence between ground-truth and spectrally-retrieved rates of crop state as well as between state indices evaluated in terms of different bioparameters. State indices can be estimated as well in relation to yield as predicted from spectral data [16].

Different growth conditions cause significant variations of plant spectral properties [13, 17-20]. The spectral response to a stress impact is seen in Fig. 3 where the measured spectral reflectance characteristics of Ni-treated spring barley plots (over grey soil) at stem elongation stage are presented.

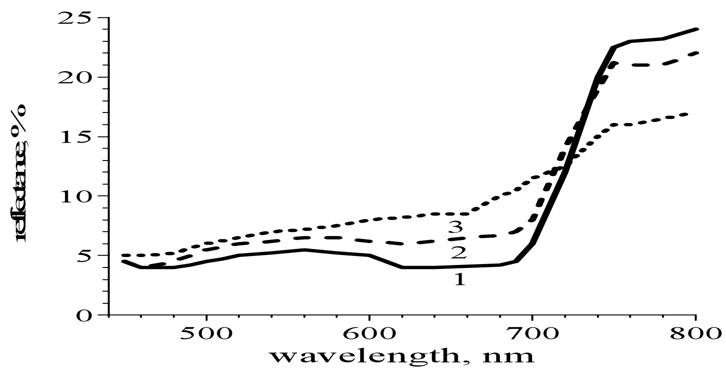



*Fig. 3. Spectral reflectance characteristics of spring barley non-polluted (1) and Ni-treated plots (2 – 200 mg/kg; 3 – 400 mg/kg) at stem elongation stage*

Plant spectral response to stress growth conditions is still better illustrated by Fig. 4 which shows the reflectance characteristics of barley control (a) and Ni-polluted (b) plots during a large portion of the growing period.

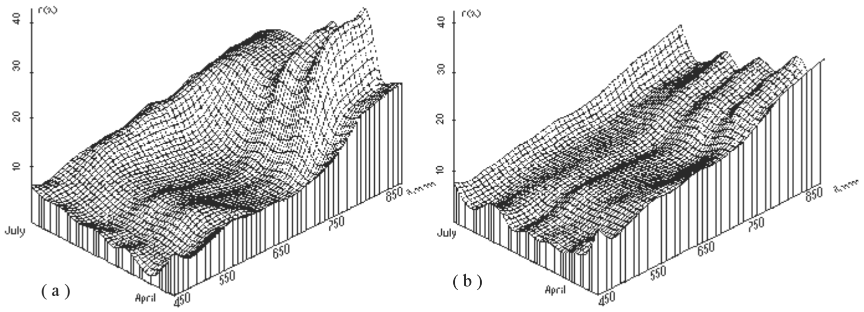



*Fig. 4. Spectral reflectance characteristics from layering till maturity of barley control (a) plots and plots with Ni concentration in the grey soil of 400 mg/kg*

The stress impact on crop growth parameters was quantitatively examined by regression analysis. Fig. 5 shows the derived dependence of barley canopy cover on the Ni contamination of the grey soil. The plots with Ni concentration of 300 mg/kg were first excluded from the regression and used later as a validation data set. As expected, predictions for the remaining data were good, moreover, the re-fit after including the validation data proved the consistency of the model.

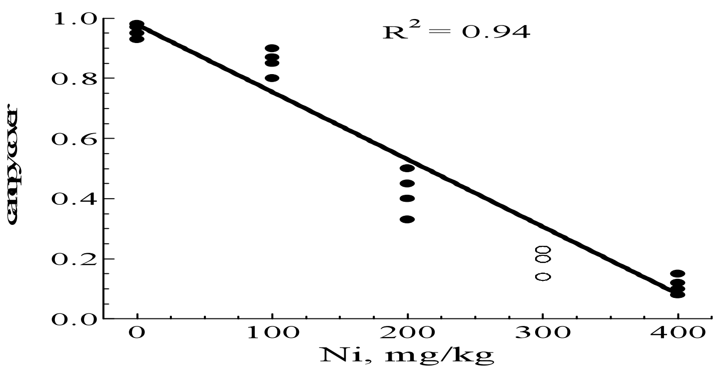
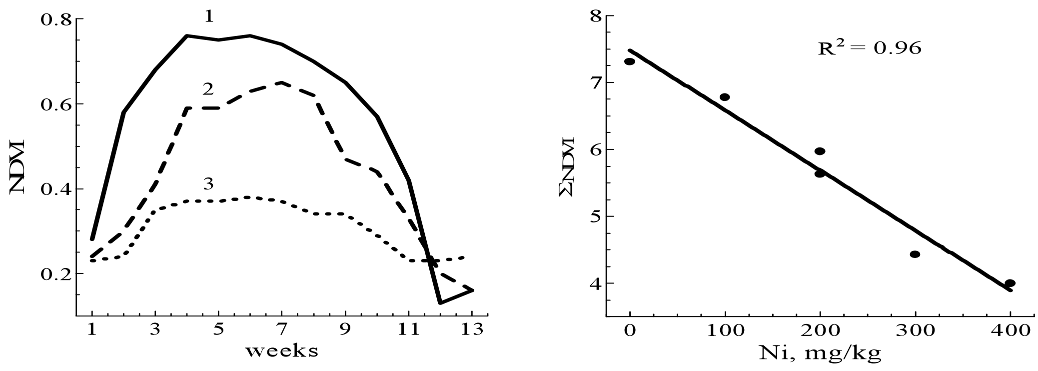



*Fig. 5. Dependence of barley canopy cover on Ni pollution*

Plant reflectance during the whole phenological period is of particular interest as it provides for the periodical evaluation of crop state. Temporal spectral data are highly indicative of variations in plant development caused by growth conditions. Fig. 6 is an example of the Ni stress impact on plant spectral features from emergence till harvest. Fig. 6a presents the temporal NDVI behaviour of barley grey soil treatments as a function of the Ni contamination. The dependence is observed throughout the entire plant growth carrying information about the current and previous plant state and showing the development trends. This fact permits early stress detection and crop diagnostics as well as forecasting of plant development process. In Fig. 6b the obtained regression of the NDVI temporal sum on the Ni concentration is given.

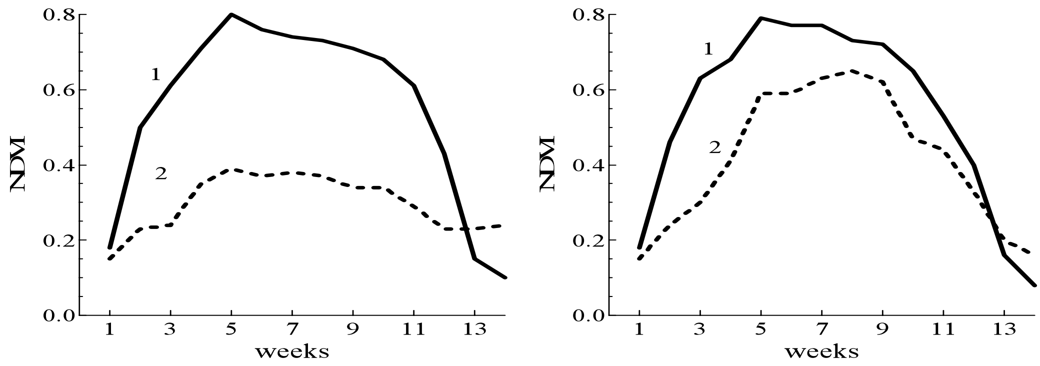
Various soil properties are factors of plant development especially when acting in combination with other growth conditions. Fig. 7 shows the temporal spectral response of spring barley on chernozem (a) and grey forerst soil (b) for control (1) and Ni-polluted plots (400 mg/kg).




a b

*Fig. 6. Dependence of barley NDVI temporal behaviour (a) and temporal sum (b) on the Ni concentration (1 - 0 mg/kg; 2 - 200 mg/kg; 3 - 400 mg/kg)*

The acidity of the grey soil increases the accessibility of the heavy metal to plants thus inhibiting their growth. The latter is clearly manifested by the different spectral behaviour during the whole plant vegetative period.




a b

*Fig. 7. NDVI seasonal profile of control (1) and equally Ni-polluted (2) spring barley plots on neutral (a) and acid (b) soil*

As crop production is a question of primary interest, barley grain yield was examined to its relationship with plant bioparameters, soil properties and stress conditions. There were not big grain yield differences between the control treatments over the two soil types. For the chernozem plots it was with about 10% higher. However, the Ni-pollution treatments over this soil were much less affected by the heavy metal than the grey soil plots. For the grey soil plots the yield was statistically related to various plant variables and spectral indices and showed strong correlations especially during the active vegetative stages (in most cases $R^2 > 0.9$). Accounting for the entire growth process, the temporal sum of various spectral indices appeared to be most closely related to plant yield [4, 21], the correlations being higher than between the yield and the spectral indices in particular phenological stages. Fig. 8 shows the fitted linear model of barley grain yield and the NDVI temporal sum during plant development period.

The nutrient supply is another factor clearly detected by plant reflectance features. Fig. 9a shows the impact of the nitrogen compound on barley NDVI temporal profiles. Equal nitrogen concentrations were applied to the plots but through different fertilizers. As seen differences in crop reflectance are observed in relation to the fertilizer compound regardless of the same nitrogen amount. This is explained most probably by the lower nitrogen accessibility to plants which worsens the nutrient supply and thus the growth conditions.

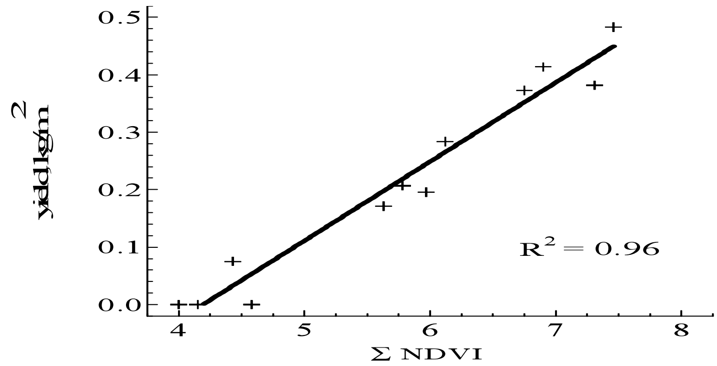
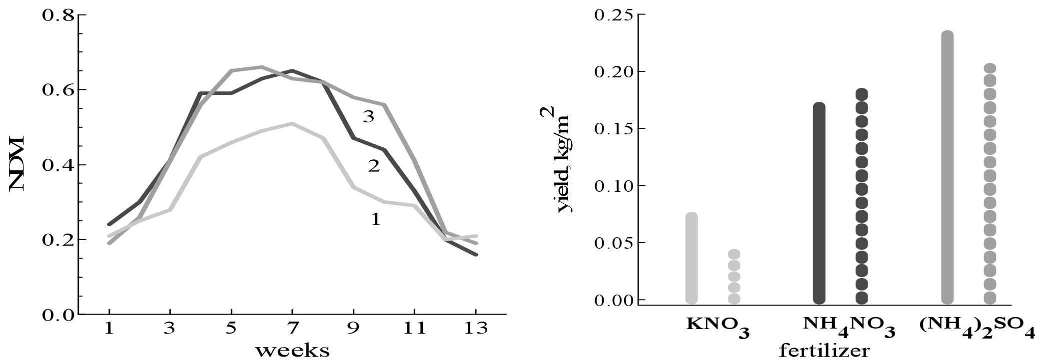



*Fig. 8. Empirical relationship between barley grain yield and NDVI temporal sum*
*Using the relationship from Fig. 8 the grain yield of these plots was spectrally predicted and compared to the actually gained. The high accuracy of the spectral prediction estimates is illustrated by Fig. 9b*




a b

*Fig. 9. NDVI temporal behaviour (a) of barley treatments with equal nitrogen concentration and different fertilizer: $KNO_3$ (1), $NH_4NO_3$ (2), $(NH_4)_2SO_4$ (3); grain yield (b) as estimated from NDVI temporal sum (---) and compared to the actual yield (—)*

## CONCLUSIONS

The obtained results show that growth conditions cause statistically significant variations of plant reflectance properties. The established empirical dependences do not only illustrate the informational potential of spectral data but attach to it a quantitative expression. Regression models relating plant spectral features to biometrical variables can be used for quantitative assessment of crop state with accuracy commensurable with ground data evaluations. The knowledge of plant parameters and their stress-induced values is essential because of the direct contribution of these parameters to potential yield. Good correspondence was observed between measured values and spectral models estimates of plant biometrical features. As it was shown, multispectral data could be successfully used in regression models for crop agrodiagnostics and assessment of growing conditions. Spectral-temporal data proved to be a good indicator of plant development process and a reliable input in yield-predicting models.

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