SPECTRAL MODELS FOR CROP STATE ASSESSMENT CONSIDERING SOIL AND ANTHROPOGENIC IMPACTS

R.Kancheva, D.Borisova
Solar-Terrestrial Influences Laboratory-BAS Bulgaria Sofia 1113 Acad.G.Bonchev Str., bl.3 - rumik@abv.bg; dborisova@stil.bas.bg

Abstract: In the contemporary world aerospace information gathered by different sensors and numerous observation missions has become a genuine necessity in various investigation and application fields. Remote sensing technologies are used for natural resources management, ecosystem change detection, environment preservation and in many other world significant problems. Vegetation monitoring is among the priorities of remote sensing being associated with plant growth assessment, stress detection, yield forecasting. This paper is devoted to the relationship between agricultural vegetation spectral and biophysical features with consideration of plant 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.

Keywords: remote sensing, vegetation monitoring, spectral reflectance, soil impact, anthropogenic factors, fertilization, heavy metal pollution, spectral-biophysical modeling

INTRODUCTION

In the contemporary world aerospace information gathered by different sensors and numerous observation missions has become a genuine necessity in various investigation and application fields. Vegetation monitoring is among the priorities of these investigations. In agriculture remote sensing is a tool that can be 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 experiment 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.

Numerous papers have the objective of retrieving quantitative information using vegetation reflective and emissive spectra. Prevailing part of them deal with green phytomass estimation, plant growth evaluation and yield prediction (Goel, 1986; Thenkabail, 1994; Clevers, 1989; Rudorff, 1990b; Shibayama, 1989). Empirical modelling appears to be one of the most widely spread tecnique for vegetation assessment (Weiser, 1986; Gardner, 1986; Malthus, 1993; Kancheva, 1992) although different conclusions have been made about the applicability of the obtained models, their dependence on local conditions and site-to-site or year-to year discrepancy. (Wiegand, 1990; Weiser, 1986)

This paper is further dedicated to spectral-biophysical modelling of agricultural vegetation considering growth conditions. The objective is to examine the impact of soil properties and anthropogenic favtors (fertilization, 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 treatments applied.

MATERIALS AND METHODS

Reflectance, biometrical and phenological data were gathered from spring barley and peas plants within a green-house experiment. The treatments (twice replicated) comprised of different soil type, heavy metal pollution and fertilization conditions. The experiment was conducted with peas grown over alluvial-meadow soil and three concentrations of Cd contamination (10, 20 and 30 mg/kg). The spring barley experiment consisted of two parts: NH_4NO_3 fertilization treatments over chernozem soil with different nitrogen concentrations (from 0 to 1000 mg/kg) including two more fertilizer compounds $Ca(NO_3)_2$ and KNO_3 for the nitrogen concentration of 800 mg/kg, and a second part of Ni-polluted barley treatments grown over dark chernozem soil (neutral with pH=7.0-7.5) and brighter grey forest soil (acid with pH=5.0-5.5) 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 were applied.

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 for barley plots and till flowering for peas. Among the various growth and ecologically relevant variables that were measured, the presented here results concern mainly plant canopy cover, above-ground biomass and yield. The reason is that variations in vegetation reflectance are most attributed to green coverage which is at the same time a primary indicator of crop state. Biomass amount is also a growth parameter 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, normalized differences as a routinely implemented data transformation (Qi, 1994; Chappelle, 1992; Penuelas, 1994). The wavelengths selected correspond to absorptions 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 consequently in spectral performance, were found associated with the impact of soil properties and anthropogenic factors.

RESULTS AND DICUSSION

Various combinations of spectral ratios (Yanev, 1994; Чимитдоржиевр 1998) were examined for their correlation with plant bioparameters and heavy metal contamination. Many of them demonstrated high R^2 values from 0.86 to 0.97. In Fig. 1 the statistical relationships of NIR/R and R/(G+R+NIR) with barley canopy cover at pre-heading stage are shown. The dependences were derived separately for grey soil (1) and chernozem soil (2) plots. If soil-integrated regression curves are used the estimation error increases almost twice, the canopy cover of the brighter soil treatments being systematically underestimated and overestimated for the dark soil treatments.

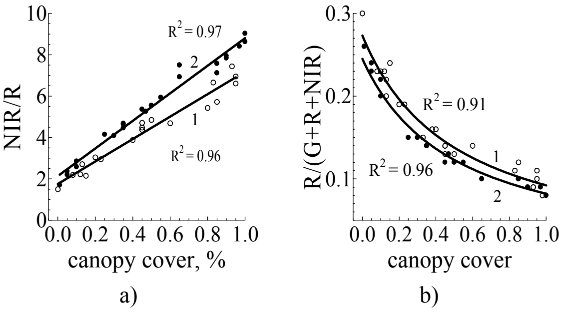


Figure 1. Dependence of barley spectral indices NIR/R (a) and R/(G+R+NIR) (b) on green canopy cover for treatments over grey (1) and chernozem (2) soil

Similar spectral models were developed for barley leaf area index. It is quite explicable considering the high correlation between the two bioparameters described in this phenological stage by the equation: LAI = −0.052+5.74×canopy cover (R^2=0.95).

Since canopy cover and leaf area index define vegetation biomass and yield potential, they can serve as crop growth and productivity indicators. Estimated from spectral data and compared to maximum (average, optimal) agronomical values for given species and climatic conditions and they can be used as "state indices", e.g. SI_{LAI} = LAI_{est}/LAI_{max}. For instance, in our experiment the maximum measured LAI at pre-heading stage of a barley unpolluted control plot over the grey soil was 5.0. For the treatment with ground-measured LAI of 2.45 the state index was SI_{LAI}=2.45/5=0.49 which means that crop state in this case was almost half worst of the best one. Further, estimation of SI_{LAI} from spectral data was performed in the following way. The obtained NIR/R for the same plot was 4.5. LAI calculated from the established regression equation LAI = −1.611+0.954×NIR/R ((R^2=0.95) was 2.68, then SI_{LAI}=0.54. So the ground-true and spectrally-estimated state indices (in terms of LAI) were close enough. Moreover, rationing the NIR/R value of the examined plot to that of the control plot (the highest measured 8.69), we obtain a state index determined by the NIR/R vegetation index SI_{VI}=4.5/8.69=0.52 which is even closer to the actual one. This example as well as the results from more test data showed a very good correspondence between ground-true and spectrally-retrieved rates of crop state as well as between state indices obtained in terms of other bioparameters.

Along with the physiological development, stress factors cause significant variations of plant spectral properties (Penuelas, 1994; Bammel, 1994; Shibayama, 1993; McMurtey, 1994; Kancheva, 1996). This is illustrated by Fig. 2 where the spectral reflectance characteristics of spring barley treatments (over grey soil) during the growth period are presented for a non-polluted plot and a plot with Ni concentration of 400 mg/kg.

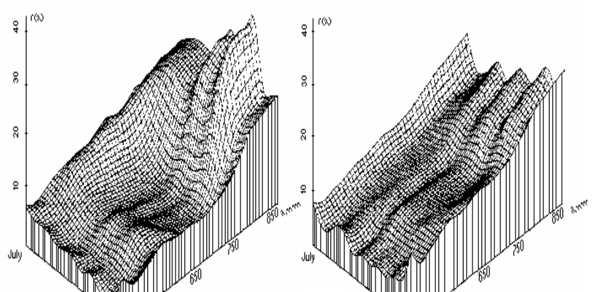


Figure 2. Spectral reflectance characteristics throughout the growing season of barley control (a) and Ni-polluted (b) plots

The contamination impact on crop growth and reflectance features was quantitatively examined by regression analysis. Fig. 3 shows the derived dependences of barley canopy cover (a) and NIR/R spectral index (b) on Ni concentration in the grey (acid) soil. The plots with Ni concentration of 300 mg/kg were first excluded from the regressions and used later as a validation data set. As expected, predictions for the remaining data were good, moreover, the test after including the validation data showed consistency of the model.

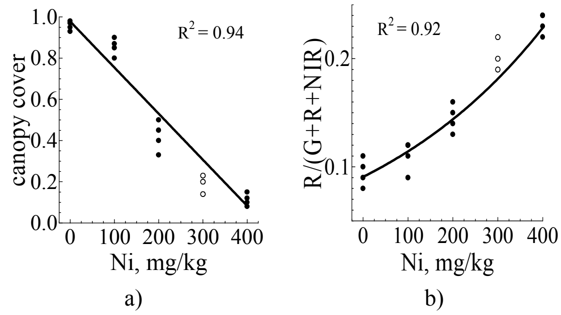


Figure 3. Dependence of barley canopy cover (a) and R/(G+R+NIR) spectral index (b) on Ni pollution

Some examples of the empirically obtained relationships between plant variables, spectral indices and Cd pollution of the peas treatments are shown in Fig. 4.

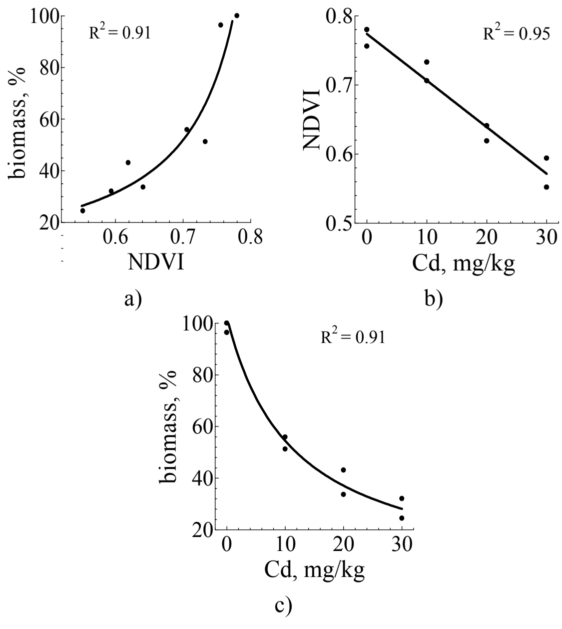
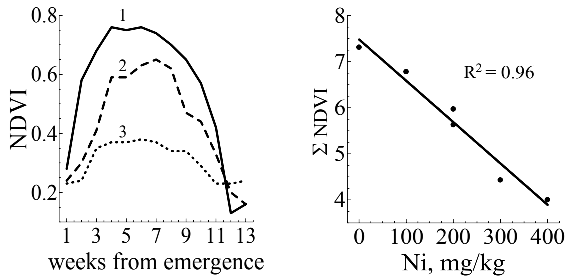


Figure 4. Statistical dependences of (NIR-R)/(NIR+R) spectral index (NDVI) on peas biomass (relative to the control treatment) (a) and Cd pollution (b); dependence of biomass on Cd pollution (c)

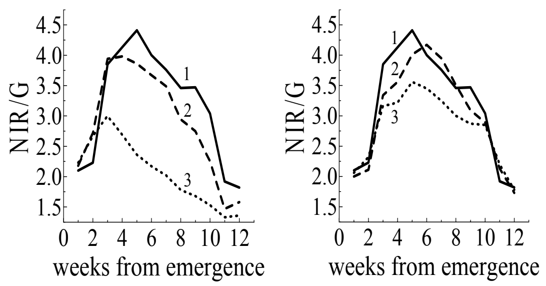
Plant reflectance behaviour during the whole phenological period is of particular interest. It provides for periodical evaluation of crop state. Temporal spectral data are highly indicative of variations in plant development caused by growth conditions. Fig. 5a presents the temporal NDVI behaviour of barley treatments over grey soil as a function of 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.5b the regression of the same spectral index temporal sum on the Ni concentration is given.



a) b)

Figure 5. Dependence of barley NDVI temporal behaviour (a) and temporal sum (b) on Ni concentration in grey soil (1 - 0 mg/kg, 2 - 200 mg/kg, 3 - 400 mg/kg)

Nutrient deficit is another stress factor clearly manifested and detected by plant reflectance features. Fig. 6a shows the impact of the nitrogen concentration on NIR/G temporal profiles of NH_4NO_3 barley treatments over chernozem soil. Differences in crop reflectance were observed also in relation to the fertilizer compound regardless of the same nitrogen amount. This is illustrated by Fig. 6b where equal nitrogen concentration of 800 mg/kg is applied but the spectral profiles of the treatments differ due to the nitrogen compound. This is explained most probably by the lower nitrogen accessability to plants which worsens the nutrient supply and thus the growth conditions.



a) b)

Figure 6. Temporal behaviour of barley spectral index NIR/G for fertilization treatments: (a) with different nitrogen concentration (1 - 0 mg/kg, 2 - 200 mg/kg, 3 - 800 mg/kg) applied through NH_4NO_3; (b) with equal nitrogen concentration (800 mg/kg) applied through NH_4NO_3 (1), KNO_3 (2) and $Ca(NO_3)_2$ (3)

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 rich organic chernozem soil it was with about 10% higher. However, the treatments over this soil in the Ni pollution experiment were much less affected by the heavy metal which did not allow statistically significant relationships or soil-integrated dependences to be developed and used for stress detection and quantitative assessment. Barley yield was statistically related to various plant variables and spectral indices and showed strong correlations especially during the active vegetative development (in most cases R^2>0.9). Accounting for the entire growth process the temporal sum of various spectral indices appears to be very closely related to plant yield (Rudorff, 1990a; Кънчева, 2000).

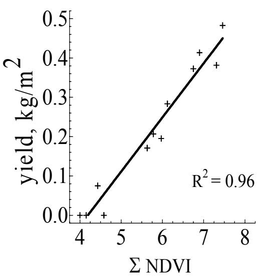


Figure 7. Empirical relationship between barley grain yield and NDVI temporal sum

In our experiment the correlations were in most cases 0.9-0.95 being higher than the correlations between yield and spectral indices in a given phenological stage. Fig. 7 presents the linear regression of barley grain yield and NDVI temporal sum during the whole development period.

Using for demonstration the same test data set as in the above presented example, the grain yield from the plot with measured LAI=2.45 at pre-heading stage was predicted using the derived equation: yield = $-0.04+0.096\times LAI$ (R^2=0.94). The obtained value of 0.195 kg/m^2 corresponds with the yield 0.217 kg/m^2 estimated by using the spectrally retrieved LAI=2.68. Further, using the temporal NDVI sum of the plot $NDVI_\Sigma=5.83$, the grain yield was determined through the dependence shown in Fig.8: yield = $-0.569+0.137\times NDVI_\Sigma$ (R^2=0.95). The value 0.230 kg/m^2 was in better agreement (relative prediction error 6%) with the actual 0.244 yield kg/m^2 t than the yield estimated (relative prediction error 20%) through the measured LAI.

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 dimension. They provide for crop monitoring and detection of stress situations as well as for evaluation of the inhibiting affect of unfavourable factors on plant growth. 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 model estimates of plant biometrical features and stress factors. 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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Acknowledgements: This research was supported by the NSFB under contracts B-1306/03 and NZ-1410/04