Optical Criteria in Estimating Deficiency of Basic Macroelements and Plant Fertilizer Requirements

V.P. Yakushev, E.V. Kanash, Yu. A. Osipov

Russian Academy of Agricultural Science, Agrophysical Research Institute
Grazhdansky prosp. 14, St. Petersburg, Russia, 195220
ykanash@yandex.ru

ABSTRACT

To ensure successful spatially differentiated fertilization, it is necessary to find a section of the field where the crop differs in appearance from that with optimal characteristics, determine the nutrient whose deficiency impaired the quality of plants in that section, evaluate the expedience of additional fertilization and calculate the amount of fertilizers needed in every individual section. Most publications on this subject are devoted to revealing crops with nitrogen deficiency while very few of them consider optical symptoms of other nutrients shortage. The aim of the present work was to study specific and nonspecific changes in optical properties and the possibility of their employment for detecting plants suffering from nitrogen, phosphorus or potassium deficiency. It was found that unbalanced mineral nutrition not only increases leaf reflectance but also induces changes in the structure of reflected radiation spectra. Appearance maximum and minimum values in reflectance spectra derivatives observed in conditions of ***N***, ***P*** and ***K*** deficiency indicates nonspecific response of plants to nutrient shortage. As has been shown, specific changes also take place under the deficiency of each of the nutrients against a background of nonspecific ones.

Keywords: Optical criteria, nutrient deficiency, wheat, fertilize, Russia

1. INTRODUCTION

Precise agriculture is the technology of the 21st century that is based on the estimation and registration of spatial and temporal heterogeneity of cultivated fields. One of the key components of this technology is precise spatially differentiated fertilization of the fields which allows to significantly lower the amount of fertilizers applied, raise the yield and improve the quality of agricultural products. This resource-saving and highly intensive technology ensures the profitability of agricultural production and reduces at the same time the hazard of environment pollution. To perform precise fertilization, it is necessary to know the distribution of nutrient elements across the field before sowing and control the provision of plants with basic nutrients when applying dressing during vegetation process. In monitoring the condition of the field before sowing the following steps should be taken:

- Detecting the section of the field where crops differ in appearance from those grown in optimal conditions which indicates that growth conditions here need improvement (detecting of faults);
- Finding out the factor that caused the deterioration of plants state in this section (determination of causes);
- Assessing the expedience of supplementary dressing and calculating the dose to be applied at every individual section (quantitative assessment).

Clearly, these three tasks are closely interrelated and the subdivision is necessary only for working out the technique of crop monitoring and spatially differentiated fertilization that would ensure the optimization of plant growth and development. The task of estimating spatial heterogeneity of the crop is rather complicated and claims close attention in elaborating methods of spatially differentiated fertilization. However, it is even harder to determine the mineral nutrient whose deficiency has caused growth retardation and to assess the amount of fertilizer to be applied.

Earlier in our studies we devised theoretical and methodical foundations of locating homogeneous technological zones for differentiated application of nitrogen fertilizers, the technique being based on remote estimation of colorimetric characteristics of the canopy in the experimental field [Yakushev, Kanash, 2011]. Following the procedure worked out, the provision of plants with nitrogen and their demand for the fertilizer were evaluated with the help of digital images of the field with specially allotted reference plots that received strictly specified doses of nitrogen. Applying various doses of nitrogen (from the maximum dose calculated for obtaining the planned yield to the minimum one, with two or three of medium value) we received crops with different colorimetric characteristics. Using three-dimensional model of colour space CIE LAB [CIE Colorimetry, 1986] we were able to assess quantitatively colorimetric characteristics of crop canopy on test plots and to plot calibration curves describing the relationship between colorimetric characteristics and a dose of nitrogen [Yakushev, Kanash, 2011]. The curves allowed us to estimate fertilizer demand of plants and the amount of fertilizer needed in each individual section of the field whose position was determined using GPS. In most of the works cited [Kokaly, 2001; Haboudane *et al* 2002; Maine *et al*, 2010] detection of the sections suffering from nitrogen deficiency was based on the observations of chlorophyll loss and/or decrease in the leaf area index. Only a few publications [Sembiring *et al*, 1998; Osborne *et al*, 2002] take into consideration optical criteria of the deficiency of other mineral nutrients.

For this reason the aim of our present work was to study specific and nonspecific changes in optical properties of plants and assess the expedience of the employment of optical criteria for detecting the deficiency of basic mineral nutrients (nitrogen, phosphorus and potassium) at early stages of its development. The experiment was carried out in controlled conditions with the purpose to exclude the unfavorable influence of factors that are not presently studied.

2. MATERIALS AND METHODS

The investigation was carried out on plants of spring wheat cultivars Leningradskaya-97 (L-97), Hester (H) and Krasnoufimskaya-100 (K-100) grown in controlled conditions on inert soil substitute (sand). The plants were showered with Knop solution (the control) or with the solution deficient in some of the macroelements (nitrogen, phosphorus or potassium). Spectral characteristics of radiation reflected from leaves (400-1000 nm) and their colorimetric characteristics were determined with Ocean Optics spectrometer HR2000 using reflection sensor R200-7-UV-VIS (Ocean Optics, USA) and the software SpectraSuite. Spectral and colorimetric characteristics in each of the experimental variants were measured on 30 plants repeating the experiment twice. Spectral characteristics were inferred from changes in reflectance indices describing the intensity and the efficiency of plant photosynthetic apparatus [Kanash, Osipov, 2009] as well as from appearance or disappearance of maximum and minimum values on the first and the second derivatives of leaf reflectance spectra. Table 1 shows the criteria that were used to estimate nitrogen, phosphorus and potassium requirements of plants.

Table 1. Criteria for evaluation changes of physiological status of plants in response to nitrogen, phosphorus and potassium deficiency

Index	Parameter measured	Computation formula	Reference
ChlRI	Content of chlorophyll, photosynthetic apparatus capacity and its ability to absorb sunlight	$\mathbf{(R_{750}\text{-}R_{705})/(R_{750}+R_{705}\text{-}2R_{445})}$	[Sims, Gamon, 2002]
***PRI**$_{mod}$*	Photochemical activity of photosynthetic apparatus. PRI was developed to assess changes in the relative level of xanthophylls and estimate the intensity of heat dissipation	$\mathbf{C^1–[(R_{570}\text{-}R_{531})/ (R_{570}+R_{531})]}$	[Peñuelas *et al*, 1995] (modified)
ARI	**A**nthocyanins content. Accumulation of A. is a sign of the oppression of plants and the inhibition of their growth	$\mathbf{C^2 + [(1/R_{550})\text{-}(1/R_{700})]*R_{750}}$	[Merzlyak *et al*, 2003] (modified)
FRI	**F**lavonols content. Accumulation of **F** is a sign of the oppression of plants and the inhibition of their growth	$\mathbf{C^3+((1/R410)\text{-}(1/R460))*R800}$	[Merzlyak *et al*, 2003] (modified)
$\boldsymbol{R_{800}}$	Indicator of light scattering. It depends on the internal structure of leaf	$\boldsymbol{R_{800}}$	[Sims, Gamon, 2002]

[1-3] values are constants determined by experiment and are usually equal 0.5-0.7.

The validity of differences between the variants was assessed by methods of parametric and nonparametric statistics using the software Excel 2010 and Statistica 8. The reliability of differences in morphophysiological and optical properties of plants for variants with different kinds of mineral nutrition was determined with the help of Kruskal-Wallis nonparametric criteria and those of Wilcoxon.

3. RESULTS AND DISCUSSION

Deficiency of nitrogen, phosphorus and potassium led to a harsh inhibition of the production process and a decrease both in leaf area (Fig. 1) and net assimilation rate NAR (Fig. 2). NAR represents a plant’s net photosynthetic effectiveness in capturing light, assimilating CO_2 and storing photoassimilate. The most pronounced inhibition of dry matter synthesis was observed in plants suffering from nitrogen deficiency. NAR in plants with nitrogen deficiency amounted on the average only to 20 percent of the control level. The influence of phosphorus and potassium deficiency was still less significant. The wheat Krasnoufimskaya-100 was less sensitive to phosphorus deficiency as compared with two other cultivars: its NAR was 65 percent of the control while with the Hester cultivar it came up to 45 percent. The cultivar Leningradskaya-97 was not so sensitive to potassium deficiency as the Krasnoufimskaya-100 and the Hester (their NAR was 75 and 55 percent of the control, respectively).

It was found that nutrient deficiency may be detected by changes in the spectra of radiation reflected from leaf surface even in the absence of apparent symptoms of plant growth retardation or of changes in leaf colour. Figure 3 presents spectral characteristics of radiation reflected from older leaves of the lower layer and from younger ones of the upper layer. As can be seen, the impact of NPK deficiency on optical properties is stronger in older leaves. Visual examination of young leaves in conditions of phosphorus or potassium deficiency did not reveal either changes in colour or other symptoms of mineral hunger which may be seen only in reflectance spectra. Phosphorus and nitrogen deficiency caused significant decrease of chlorophyll concentration, especially in the lower layer leaves of all cultivars studied (Fig. 1). In case of potassium deficiency, however, probable changes of chlorophyll index were observed only in cultivars Hester and Krasnoufimskaya-100 and were absent in Leningradskaya-97.

Table 1 demonstrates results of assessing the probability of difference in optical characteristics between plants grown under optimal nutrition and under the deficiency of one of the macroelements. The table lists 6 indices including the index of chlorophyll content in the leaf that shows the potential of a plant to absorb light. Other indices make it possible to assess the efficiency of absorbed light participation in photochemical processes of photosynthesis. Changes of these indices are the only symptom of plant stress when either outward signs of mineral deficiency or loss of chlorophyll are not observed yet. As can be seen, optical characteristics of the given wheat cultivars change differently.

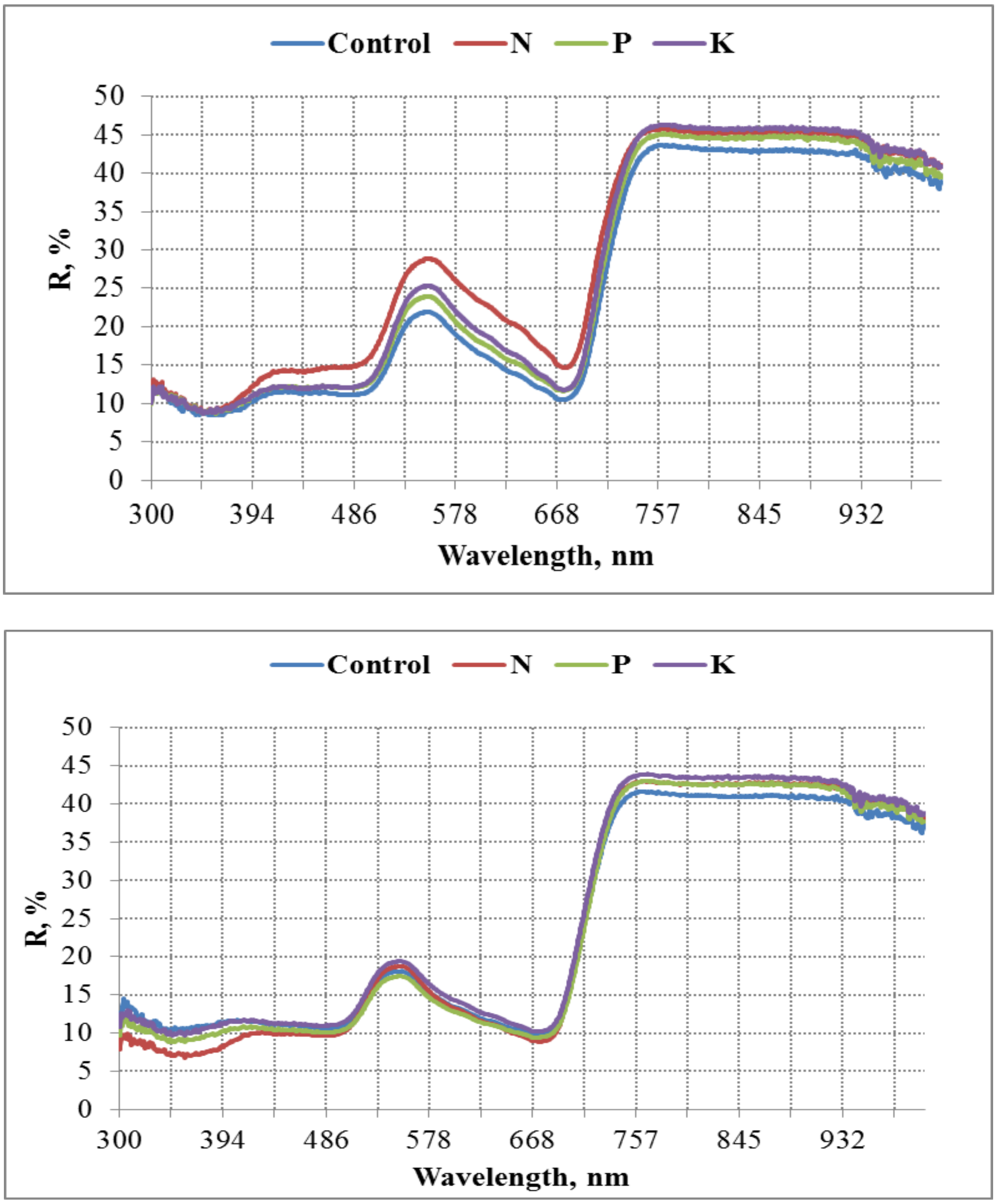

Figure 1. Spectral characteristics of radiation reflected from leaves of lower (at the top) and upper (at the bottom) layers in conditions of optimal mineral nutrition (Control) and under the deficiency of nitrogen (N), phosphorus (P) or potassium (K).

Common to these cultivars is the absence of changes in the value of heat dissipation index HDRI under potassium deficiency (see the table). In conditions of nitrogen or phosphorus deficiency part of light energy unutilized in photosynthesis dissipates in the form of heat produced during carotenoids conversion. Increase of the heat dissipation index is a sign of these changes. Therefore, plant growth inhibition not accompanied by any changes of HDRI suggests that the plants are suffering from potassium deficiency.

As has been found, nutrient deficiency promoted the accumulation of some phenolic compounds whose total content was determined from the values of anthocyanins and flavonols indices (ARI and FRI). In wheat plants with phosphorus and potassium deficiency, the highest values of ARI and FRI were observed in young intensively growing leaves while under nitrogen deficiency such changes occurred in older leaves.

Table 1. The validity of difference in optical properties between plants grown in optimal conditions of mineral nutrition and those suffering from the deficiency of one of basic macroelements. The table shows significance levels *p*; red type indicates statistically improbable differences between control values (optimal mineral nutrition) and those of variants with the deficiency of nitrogen (N), phosphorus (P) or potassium (K).

Index	Deficiency of the element	Cultivar		
		L-97	K-100	H
ChlRI	N	0,000002	0,000003	0,000003
	P	0,000004	0,000006	0,000002
	K	0,1204	0,000002	0,000003
R800	N	0,5304	0,22102	0,00316
	P	0,9426	0,81302	0,000003
	K	0,014	0,0495	0,000003
HDRI	N	0,000002	0,000002	0,000002
	P	0,000069	0,00361	0,53044
	K	0,2452	0,97539	0,53044
ARI	N	0,000014	0,000006	0,000002
	P	0,0073	0,01657	0,000002
	K	0,6143	0,000002	0,000002
FRI	N	0,00042	0,000034	0,000002
	P	0,1414	0,03683	0,000016
	K	0,3086	0,70356	0,02431

The results obtained indicate that reliable estimation of plant demand for fertilizers requires the employment of several criteria of plant condition assessment. Incomplete mineral nutrition not only increases the reflectance of leaves but also causes changes in spectral characteristics of reflected radiation which can be observed, along with changes of reflectance indices, in analyzing the appearance of maximum and minimum values in reflectance spectrum derivatives. Comparison of wavelengths corresponding to these maxima and minima indicates specific and nonspecific changes in optical properties of leaves caused by the deficiency of one of the macroelements. Besides nonspecific changes there was observed the appearance of the same maximum and minimum values in reflectance spectrum derivatives under the deficiency of each of the three macronutrients (Table 2).

Table 2. Nonspecific changes in spectral characteristics of radiation reflected from leaf surface caused by the deficiency of all three macroelements. Specific changes in spectral characteristics of radiation reflected from leaf surface caused by the deficiency of one of the three macroelements: nitrogen (N), phosphorus (P) or potassium (K).

Deficiency of N,P or K (nonspecific changes)			
SR*	λ, nm	max	min
	389	+	
	393	+	
	404		+
	405	+	
	406	+	
	408		+
	409	+	
	413	+	
	419		+
	425		+
	440	+	
	452	+	
	467		+
	490		+
	508	+	
	539		+
	686	+	
	714		+
	720		+
	721		+
	725		+
	730		+
	734		+
	739		+

Deficiency of N			
SR	λ, nm	max	min
	388		+
	400	+	
	412	+	
	430	+	
	477		+
	487		+
	489	+	
	526	+	
	529	+	
	537	+	
	550		+
	554		+
	568		+
	572		+
	579		+
	590		+
	602		+
	609		+
	615		+
	628		+
	646		+
	664		+
	689	+	
	699	+	

Deficiency of P			
SR	λ, nm	max	min
	392		+
	403	+	
	415		+
	416	+	
	422		+
	424	+	
	443	+	
	448	+	
	509		+
	544	+	
	564	+	
	679		+
	685		+
	695		+
	712		+
	719	+	

Deficiency of K			
SR	λ, nm	max	min
	410		+
	435	+	
	438		+
	482		+
	663		+
	706	+	

* - SR – spectral range in which there are additional maximums and minimums.

Changes in optical properties due to nutrient deficiency were both nonspecific and specific for a given macroelement. Spectral characteristics changed most markedly under nitrogen deficiency (most of new maxima and minima were observed in the first derivatives of reflectance spectra). Under deficiency of phosphorus and particularly of potassium the changes were much less. It was found that on returning to the optimal nutritive regime the growth rate and optical properties of plants with potassium and phosphorus deficiency restores almost completely while in plants with nitrogen deficiency this process goes on more slowly. The experimental data obtained allow to draw a conclusion that optical methods make it possible to reveal both nonspecific and specific changes taking place due to the deficiency of each of the three macroelements:

nitrogen, phosphorus and potassium. High-resolution spectral characteristics of radiation reflected from leaf surface indicate differences between plants suffering from the deficiency of each of the elements even in the absence of visible signs of plant hunger.

4. REFERENCES

CIE Colorimetry, 1986. Publication CIE no 15.2, Central Bureau of Commission Internationale de L'Eclairage, Vienna, Austria, 2nd edition.

Haboudane, D., Miller J. R., Tremblay N., Zarco-Tejada P. J., Dextraze L., 2002. Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture. *Remote Sensing of Environment*, 81: 416-426.

Kanash E.V., Osipov Ju.A. 2009. Optical signals of oxidative stress in crops physiological state diagnostics. Precision agriculture 2009. Wageningen Academic Publishers, P. 81-89.

Kokaly R.F. 2001. Investigating a Physical Basis for Spectroscopic Estimates of Leaf Nitrogen Concentration. *Remote Sensing of Environment* 75: 153–161.

Maine, N., Lowenberg-DeBoer, J., Nell, W.T., Alemu Z.G. 2010. Impact of variable-rate application of nitrogen on yield and profit: a case study from South Africa. *Precision Agriculture* 11 (5): 448-463.

Merzlyak M.N. A.A. Gitelson, O.B. Chivkunova, A.E. Solovchenko and S.I. Pogosyan, 2003. Application of reflectance spectroscopy for analysis of higher plant pigments. *Russian Journal of Plant Physiology* 50: 704-710.

Osborne S. L., Schepers J. S., Francis D. D., Schlemmer M. R. 2002. Detection of Phosphorus and Nitrogen Deficiencies in Corn Using Spectral Radiance Measurements. *Agronomy Journal* 94: 1215–1221.

Peñuelas J., Baret F., Filella I. 1995. Semi-empirical indices to assess carotenoids/chlorophyll a ratio from leaf spectral reflectance. *Photosynthetica* 31(2): 221-230.

Sembiring, H., W.R. Raun, G.V. Johnson, M.L. Stone, J.B. Solie, and S.B. Phillips. 1998. Detection of nitrogen and phosphorus nutrient status in bermudagrass using spectral radiance. Journal of Plant Nutrition 21: 1189–1206.

Sims D.A., Gamon J.A. 2002. Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. *Remote Sensing of Environment* 81 (2-3): 337-354.

Yakushev V. P., Kanash E.V. 2011. Evaluation of plants nitrogen status by colorimetric characteristics of crop canopy presented in digital images // Precision Agriculture 2011, edited by John V Stafford Ampthill, UK. 8th European Conference on Precision Agriculture, Prague, Czech Republic 11-14 July 2011, pp. 341-351.