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GRAIN PRODUCTION AND OPTICAL CHARACTERISTICS IN THREE WHEAT (*Triticum aestivum* L.) VARIETIES UNDER LIMING AND NITROGEN FERTILIZATION

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Abstract

Liming of acidic soils occupying 73 million hectares of agricultural land in the Russian Federation is a traditional technique that provides optimization of soil conditions and contributes to obtaining high and stable yields. The cultivation of crops with intensive technologies is accompanied by the export of calcium with a yield, washing out with atmospheric precipitation, etc., so it is necessary to replenish calcium, which is economically costly. Knowing the optimum dosages for each type of ameliorant is necessary to adjust its quantity which provides the maximum effect from the application. For the first time, effect of various doses of ameliorant (limestone meal-dolomite) was evaluated in situ by the optical characteristics of spring wheat (*Triticun aestivum* L.) cultivars Leningradskaya 97, Krasnoufimskaya 100 and Trizo differing in grain productivity and responsiveness to nitrogen fertilizer application. Plants were grown in 5 litre containers with sod-podzolic soil, in natural light. The rates of applied ameliorant were 0 (control), 0.25, 0.50, 0.75 and 1.00 Hy (mmolc 100 g^{-1}). Nitrogen (ammonium nitrate) was applied before seeding in two doses: optimal (1 g N) and deficit (0.15 g N) nutrition level in 5 kg of soil. The content of other mineral nutrients in the soil was similar in all cultivars of the experiment. Spectral characteristics of radiation reflected from leave surface (300-1000 nanometers) were registered by a spectrometer HR2000 («Ocean Optics», USA). After reflection spectra recording, the spectral reflection indexes closely related to chlorophyll content, the ratio between the amount of carotenoids and that of chlorophylls, the light dispersion caused by changes of inner leaf structure, the activity of the photochemical processes of photosynthesis, anthocyanins and flavonols content were calculated. The results indicate that wheat cultivars respond differently to ameliorant and its favourable effect on plants productivity is more expressed under nitrogen deficiency. In response to ameliorant application at the optimum level of nitrogen supply, grain yield of cv. Leningradskaya 97 has not changed. Grain production of cv. Triso was higher throughout the range of application doses. Range of a positive response to the impact of ameliorant of cv. Krasnoufimskaya 100 was narrower in comparison to cv. Trizo and shifted toward lower doses. Close correlation between the grain yield under different ameliorant doses and the content of chlorophyll in the leaves (chlorophyll index) for the Krasnoufimskaya 100 ($R^2 = 0.87$) and Trizo ($R^2 = 0.88$) was found. Changes in the indices which characterize efficiency of light energy conversion in the photochemical processes of photosynthesis, allows us to suggest that the ameliorant introduction not only promotes nitrogen absorption but also affects the efficiency of light energy use through photosynthesis.

Keywords: ameliorant, wheat, grain production, nitrogen fertilizer, optical and morpho-physiological properties

In Russia, acid soils occupy 73 million hectares of agricultural lands [1], and liming is conventional method to optimize soil conditions for obtaining high and stable yields [2-5]. To date, in the Russian Federation area of ameliorative lands has reduced from 6 million to 266 thousand hectares [6]. On agricultural soils with high acidity, about 20 million tons of grain products are not annually harvested, and the payback of nitrogen fertilizers on strongly acidic soils is 1.4-2.7

times lower than on slightly acid and neutral soils [3, 6]. Intensive crop cultivation is accompanied by removing calcium with yield. According to summarized data, the annual calcium removal from soil by different species varies from 20 to 500 kg/ha [7]. In soils of the Non-Chernozem zone, atmospheric precipitations affect negatively the calcium balance. According to long-term research data, the average annual calcium losses from sod-podzol soils because of rains are 300-400 kg/ha [8]. Appreciation ща amelioration leads to the fact that the amount of introduced lime with calcium agents compensates only 6-8 % of its natural losses. Complete rejection of liming caused passing a significant part of neutral soils to the slightly acid category and slightly acid to the medium and strongly acidic categories [9].

Different response of wheat varieties to liming and their genetic heterogeneity are available resources that can ensure a reduction in crop losses caused by the soil acidity. It is shown that some wheat varieties can tolerate more acidic soil, while others are very sensitive to such conditions [10-12]. Screening for tolerance to soil acidity of 116 wheat genotypes, including commercial varieties and breeding lines from Western Australia, identified some cultivars which significantly exceeded well-known cultivated varieties in this trait [12]. Improving the situation by the genetic plant improvement for tolerance to soil acidity can be considered not only alternative to the lime or other soil-ameliorative methods, but as an auxiliary tool. Identification of responses to liming in a particular variety is necessary for the most effective ameliorant application [13]. Such approach will significantly reduce the costs for acid soil liming.

It is generally accepted that the phenotyping of economically valuable traits, such as productivity and tolerance to the abiotic stressors, is the most laborious and technically difficult because of testing in different environmental conditions for several seasons. Some of the available methods are based on the destructive sampling during different stages of plant growth, take much time and resources. In this context, new phenotyping methods with high throughput have been developed in the last decades, e.g. non-invasive imaging, spectroscopy, image analysis and high-performance computing [14, 15].

Earlier, using contact and proximity diagnostics of plants physiological state in situ, we tested a number of optical criteria (reflection indexes) for assessment of barley and wheat tolerance to different stressors, including UV radiation, water and nitrogen shortage [16-18], and also for quantitative estimates of plant requirements in nitrogen fertilizers [19]. The obtained results showed that this method reveals disorders in plants at the earliest growth stages and can be used for improving agrotechnologies and yield forecasting.

In this paper, the influence of different doses of ameliorant (dolomite flour) is evaluated for the first time in situ by optical characteristics of leaves for wheat varieties which differ in productivity and response to the nitrogen fertilizers. The optimal dosage for each variety provides the maximum effectiveness of the ameliorant application.

The aim of the paper was to find out optical criteria suitable to assess the response of spring wheat varieties grown in the northwest of the Russian Non-Chernozem zone under liming, for studying effect of the ameliorant in a wide range of doses and identification of its optimal dose for each variety depending on nitrogen nutrition.

Techniques. In the tests we used three spring wheat *(Triticum aestivum* L.) varieties, Krasnoufimskaya 100, Leningradskaya 97 and Trizo, which differ in productivity and a response to nitrogen fertilizers. The substrate was acidic (pH 4.1) sod-podzolic light loamy soil with high exchangeable aluminum and low humus content (1.9 %), hydrolytic acidity (H_h) of 4.7 mmol(eq)/100 g, Ca^{2+} of 1.75 and Al^{3+} of 0.6 mmol/100 g; the particles < 0.01 mm in size made 24.7 %.

Plants were grown in 2012 under natural light in a greenhouse containers (5 kg of soil in each) covered with plastic film. In 2012, the average monthly temperature exceeded the norm by 1.4 and 0.7 °C in May and July, and was 0.4 °C lower in August. Watering was carried out daily, soil moisture was maintained at 75±5 % of the total available soil water (TAW). Experimental design included 21 variants which differed in soil nitrogen content and hydrolytic acidity. To create different levels of nitrogen, ammonium nitrate was applied before seeding in two dosages of nitrogen, i.e. 1 g for optimal nitrogen nutrition (ONN) and 0.15 g for deficit nitrogen nutrition (DNN). The ameliorant (dolomite flour with 85 % neutralizing capacity) doses were 0 (control), 0.25; 0.50; 0.75 and 1.0 H_h. At ONN, all three verities were tested in all four liming regimes. At DNN, 0 (control), 0.50 and 1.0 H_h were tested in Krasnoufimskaya 100 and Trizo varieties, which according to preliminary data are more responsive to the ameliorant compared to Leningradskaya 97 variety. Twenty seeds were sown into each container. After emergence of seedlings, the number of plants was leveled to 12 plants per container. Plant productivity was assessed after reaching full ripening. Experiment was arranged in 4 replications.

The reflection spectra of leaf surface were registered at stem elongation and beginning of tillering in the middle parts of leaves 4 and 6 using fiber optic spectrophotometric system (Ocean Optics, USA). At least 18 spectra for each variant were recorded. The reflected radiation spectra were used to measure the light scattering by leaves R_{800} [6] and to calculate the reflection indices (chlorophyll content ChlRI, ratio of carotenoids to chlorophyll SIPI, photochemical activity of the photosynthetic apparatus PRI, content of anthocyanins ARI and flavonols FRI) characterizing the activity of the photosynthetic apparatus:

$$ChlRI = (R_{750} - R_{705})/(R_{750} + R_{705} - 2R_{445})\ [20],$$
$$SIPI = (R_{800} - R_{445})/(R_{800} - R_{680})\ [21],$$
$$PRI = (R_{570} - R_{531})\ (R_{570} + R_{531})\ [21],$$
$$ARI = R_{750}\ (1/R_{550} - 1/R_{700})\ [22],$$
$$FRI = [(1/R_{410}) - (1/R_{460})] \times R_{800}\ [23],$$

where R is reflection index, figures are the wavelength reflected from the leaf surface.

For ease of the data interpretation and obtaining of positive values of reflection indexes, for all test variants, a constant C value was introduced into the PRI, ARI and FRI formulas, from which the values of these indices were deducted. The modified reflection indices are $PRI_{mod} = C_1 - PRI$, $ARI_{mod} = C_2 - ARI$, $FRI_{mod} = C_3 - FRI$. The value of C_1-C_3 was defined experimentally. Usually, C_1 value for wheat plants grown under natural light was 0.5; C_2 and C_3 were 0.7 [16, 17].

The statistical processing was performed with Statistica 8 (StatSoft, Inc., USA) software and Excel 2010. Mean values (*M*), standard errors of mean (±SEM) and confidence range at 95 % confidence level ($t_{0,05} \times$ SEM) were determined. Significance of differences between the variants was assessed by the parametric (Student's t-test) and non-parametric (the Wilcoxon pair comparison test) statistics methods. Differences between variants were statistically significant at $p \leq 0.05$.

Results. The applied optical indices make it possible to estimate the capacity (intensity) of the photosynthetic system (ChlRI is the chlorophyll reflection index which is determined by the leaf content of chlorophyll and most closely correlates with the content of chlorophyll per unit of leaf area), and the efficiency of light energy conversion in photochemical processes of photosynthesis (SIPI is the ratio of total carotenoids to total chlorophylls, PRI is the efficiency of photosynthetically active radiation, ARI is the content of anthocyanins; R_{800} is criterion of light scattering which depends on the surface characteristics and leaf structure).

Plants of Leningradskaya 97, Krasnoufimskaya 100, and Trizo varieties responded differently to the ameliorant (Fig. 1). The increased grain yield (12±3 %, $p \leq 0.039$) was identified in Leningradskaya 97 variety only at H_h 0.75

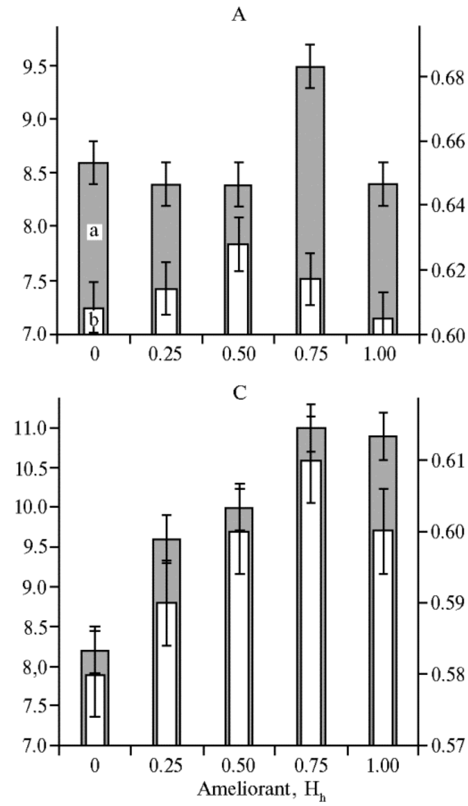

Fig. 1. Grain weight per plant, g (a, left axis) **and chlorophyll ChlRI content, relative unit** (b, right axis) **in leaves of upper layer of wheat (*Triticum aestivum* L.) plants at tillering depending on ameliorant doses under optimal nitrogen supply:** A — Leningradskaya 97 variety, B — Krasnoufimskaya 100 variety, B — Trizo variety (greenhouse trial, 4-fold replications). Mean values and confidence range are presented, $M \pm (t_{0.05} \times \text{SEM})$.

dose of the ameliorant, while lower and higher doses did not affect the yield significantly. Krasnoufimskaya 100 plants were the most responsive to the impact of ameliorant, with an increase in the productivity by more than 30±3 % ($p \leq 0.024$) after the lowest dose of the ameliorant (0.25 H_h). A dose of 0.50 H_h also increased the yield of this variety by 30±2 % ($p \leq 0.009$). A higher dosage (1.00 H_h) had a significant but lower effect, and the grain yield became higher by 20±3 % ($p \leq 0.041$). The maximum yield increase for Trizo variety, equal to about 30 %, occurred after application of the ameliorant at 0.75 and 1.00 H_h. This variety responded positively to significantly lower doses (0.25 and 0.50 H_h), increasing the grain yield by 17±2.4 % ($p \leq 0.033$) and 24±2.1 % ($p \leq 0.021$), respectively. Thus, Leningradskaya 97 variety plants respond positively to relatively high dose of the ameliorant (0.75 H_h) while other doses are ineffective. Grain yield of Krasnoufimskaya 100 variety increases at all applied doses, but most significantly at 0.25 H_h whereas productivity of Trizo variety increases as the ameliorant dose elevates. It can be assumed that such a different response to the ameliorant is due to origin of varieties and properties of soils on which the plants were grown during breeding.

Changes in the wheat plants productivity depending on the ameliorant dose and nitrogen nutrition are shown in Figure 2. At ONP and 0.50 H_h ameliorant the grain weight per plant of Krasnoufimskaya 100 and Trizo varieties increased by 30 and 22 % ($p \leq 0.040$), respectively. At the same nitrogen level, an increase of the ameliorant dose to 1.00 H_h did not lead higher productivity of Krasnoufimskaya 100 variety, but increased grain weight in Trizo variety by 35 % ($p \leq 0.035$). In DNS and medium dose of the ameliorant (0.50 H_h), the grain weight increased by 15 % ($p \leq 0.041$) in Krasnoufimskaya 100 and did not change in Trizo plants. Grain yields of Krasnoufimskaya 100 and Trizo varieties with the 1.00 H_h ameliorant were respectively higher by 8±2 % ($p \le 0.032$) and 25±3 % ($p \le 0.021$) compared to control (ONN) (see Fig. 2). It can be concluded that in the case of a nitrogen nutrition deficiency, the ameliorant application will improve nitrogen assimilation, and to maximize the effect the ameliorant dose for Krasnoufimskaya 100 should be significantly less than for Trizo plants. Regardless of the nitrogen nutrition level, Krasnoufimskaya 100 plants are capable of the greatest yield increase with the ameliorant at 0.50 H_h. Further elevation of the ameliorant dosage does not provide an increase in grain productivity. In Trizo variety, irrespectively of the nitrogen supply, both the highest doses of the ameliorant (1.00 and 0.50 H_h) promote a significant yield increase.

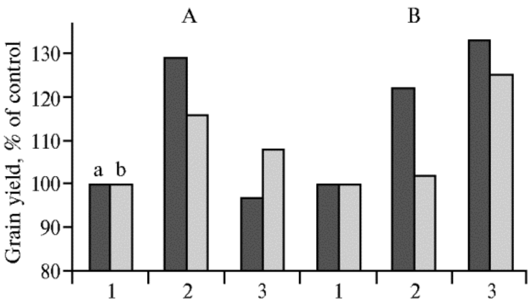

Fig. 2. **Grain weight in Krasnoufimskaya 100** (A) **and Trizo** (B) **wheat *(Triticum aestivum* L.) plant varieties as influenced by the ameliorant and nitrogen nutrition:** a — optimal nitrogen nutrition (ONN), b — deficient nitrogen nutrition; 1 (control) — without ameliorant, 2 and 3 — the ameliorant at 0.50 and 1.00 H_h, respectively (greenhouse trials, 4-fold replications). The average values are given, the grain yield without ameliorant (1) is 100 %. Confidence intervals $M \pm (t_{0.05} \times \text{SEM})$ do not exceed ±5 % ($p \le 0.05$).

The ameliorant stimulates chlorophyll synthesis (see Fig. 1) and an increase in assimilating leaf area and the percentage of leaf biomass from total plant biomass (Table 1), thus providing more active photosynthetic apparatus. Irrespectively of nitrogen supply, soil modification promotes to a significant increase in chlorophyll content. At ONP, the maximum chlorophyll increase in Krasnoufimskaya 100 variety was with 0.50 H_h of the ameliorant. Further elevation of the dose (up to 1.0 H_h) did not increase this pigment content. The Trizo variety responded positively to the ameliorant throughout the doses used: the amount of chlorophyll increased as the ameliorant dose increased regardless of nitrogen nutrition level (see Fig. 1).

1. Morphophysiological indices of wheat (*Triticum aestivum* L.) plants at earing as influenced by the ameliorant and nitrogen nutrition (greenhouse trials, 4-fold replications)

Dose, H_h	N, g per pot	ALA		Parts/plant					
				leaves		stems		ears	
		cm^2	%	g	%	g	%	g	%
Krasnoufimskaya 100 variety									
0 (control)	1	82.8	100.0	0.25	100.0	0.55	100.0	0.19	100.0
0.25	1	111.8	135.1	0.30	119.8	0.42	76.7	0.18	98.3
0.50	1	103.1	124.5	0.28	111.9	0.50	92.1	0.14	72.7
0.75	1	84.9	102.6	0.28	112.1	0.49	90.1	0.14	72.7
1.00	1	87.0	105.1	0.32	127.6	0.42	76.5	0.06	34.4
0 (control)	0.15	76.0	100.0	0.22	100.0	0.47	100.0	0.18	100.0
0.50	0.15	91.4	120.3	0.28	126.5	0.45	95.4	0.13	75.6
1.00	0.15	72.9	96.0	0.27	120.9	0.45	94.8	0.13	72.5
Trizo variety									
0 (control)	1	92.6	100.0	0.29	100.0	0.39	100.0	0.16	100.0
0.25	1	107.1	115.6	0.35	117.9	0.47	118.9	0.14	87.3
0.50	1	108.5	117.2	0.35	118.1	0.39	100.1	0.10	63.6
0.75	1	111.8	120.8	0.37	127.8	0.39	100.6	0.11	64.8
1.00	1	118.5	128.0	0.36	123.3	0.40	100.7	0.13	77.2
0 (control)	0.15	93.5	100.0	0.30	100.0	0.47	100.0	0.17	100.0
0.50	0.15	106.4	113.8	0.31	104.3	0.45	105.7	0.13	84.7
1.00	0.15	115.9	124.0	0.32	105.1	0.39	90.7	0.12	77.3

Note. ALA — assimilating leaf area. For ALA and biomass, a percentage for the control variant is indicated (for each of the varieties and for each of the doses of nitrogen) in which the ameliorant was not applied. Confidence intervals $M \pm (t_{0.05} \times \text{SEM})$ do not exceed ±5 % ($p \le 0.05$).

Determination coefficient (R^2) for the relationship between grain weight and the chlorophyll index (ChlRI) was $R^2 = 0.87$ (p = 0.020) for Krasnoufimskaya 100 variety and $R^2 = 0.81$ (p = 0.018) of Trizo increased. For Leningradskaya 97 variety, no relationship was found between the grain weight per plant and the chlorophyll content ($R^2 = 0.008$, p = 0.88).

For Krasnoufimskaya 100 and Trizo varieties at ONN, the leaf biomass increased with the ameliorant dose growth. The ameliorant application at the nitrogen deficiency led to an increase in the leaf biomass for the Krasnoufimskaya 100 variety, with the maximum value at 0.50 H_h (see Table 1). No significant effect of the ameliorant doses upon leaf biomass was identified in Trizo plants under nitrogen deficiency. It is characteristic that the doses of the ameliorant (0.25 and 0.75-1.00 H_h, respectively), causing in Krasnoufimskaya 100 and Trizo plants under optimal nitrogen nutrition the highest increase in the assimilating leaf area, leaf biomass, the chlorophyll content (ChlRI), and the grain yields, coincide.

Leaf area growth under the ameliorant application at optimal nitrogen nutrition resulted in a decrease in stems biomass, mostly for Krasnoufimskaya 100 variety (see Table 1). At nitrogen deficit, the stem biomass decreased insignificantly in response to the ameliorant application. The biomass of green ears of Krasnoufimskaya 100 and Trizo plants by the time of sampling was lower after the ameliorant application. These results show that the ameliorant, by optimizing plant nitrogen nutrition, promotes leaf growth and delays aging, which inhibits transition to heading and modulates ear growth. Similar processes can be observed with a high level of nitrogen nutrition. The formation of a powerful photosynthetic apparatus, able to keep up the photosynthesis activity for more prolonged time, gives undoubted advantages for realizing the potential of plants productivity. However, it may be supposed that the negative consequences of such changes, apparently, will be some elongation of the growing season and a tendency to lodging plants because of weaker stems.

2. Optical properties of wheat (*Triticum aestivum* L.) leaves as influenced by the ameliorant and nitrogen nutrition ((greenhouse trials, 4-fold replications)

Variant	Ameliorant dose, H_h	Nitrogen level	ChlRI	SIPI	R_{800}	PRI_{mod}	ARI_{mod}	FRI_{mod}
		Krasnoufimskaya 100 variety						
1	0	ONN	0.530	1.019	30.90	0.462	0.557	3.797
2	0.50	ONN	0.557*	1.020	30.86	0.470	0.479*	4.586*
3	1.00	ONN	0.521	1.014*	30.25	0.472	0.496	3.152
4	0	DNN	0.525	1.014	30.39	0.445	0.455	3.737
5	0.50	DNN	0.537	1.014	31.91*	0.476*	0.502	2.982
6	1.00	DNN	0.543	1.012	32.25*	0.494*	0.487	3.636
		Trizo variety						
7	0	ONN	0.590	1.009	31.84	0.445	0.428	3.561
8	0.50	ONN	0.590	1.008	32.26	0.448	0.443	2.855*
9	1.00	ONN	0.604*	1.011	33.67*	0.448	0.532*	2.551*
10	0	DNN	0.582	1.009	31.85	0.435	0.385	3.992
11	0.50	DNN	0.596	1.012	31.74	0.423	0.425	3.937
12	1.00	DNN	0.606*	1.011	32.89*	0.448	0.474	3.658

Note. ONN and DNN — optimal and deficit nitrogen nutrition. Reflection indexes: ChlRI — chlorophyll content, SIPI — carotinoids/chlorophyll ratio, R_{800} — light scattering within the leaf, PRI_{mod} — photochemical activity, characterizing intensity of heat dissipation, ARI_{mod} and FRI_{mod} — contents of anthocyanins and flavonols. For formulas to calculate the indexes, see the "Techniques" section. For statistical processing a nonparametric Wilcoxon test was applied with pairwise comparison of the variants 1 and 2, 1 and 3; 4 and 5, 4 and 6; 7 and 8, 7 and 9; 10 and 11, 10 and 12.

* Differences for corresponding pairwise comparison are statistically significant at $p \leq 0.05$.

Optical characteristics of leaves of Krasnoufimskaya 100 and Trizo plants differ and vary depending on the nitrogen nutrition and the ameliorant doses (Table 2) with different sensitivity of the indexes to these factors. The maximum chlorophyll (ChlRI) content for both varieties was noted at the same ameliorant doses which were also necessary for the greatest increase in the grain yield (0.25

H_h for Krasnoufimskaya 100 and 0.75-1.00 H_h for Trizo).

Estimation of photosynthetic activity by the amount of chlorophyll does not always allow true assessment of the physiological state of plants. For example, in studying response of wheat and barley plants of different varieties to the action of ultraviolet radiation (λ = 280-380 nm), it was shown that a relationship between the reflection index of chlorophyll and the net production value is notable only under apparent growth inhibition [16-18]. Most likely, a small chlorophyll loss is aimed at creating conditions to restrict the effects of oxidative stress, and this is not always accompanied by growth inhibition and yield losses [16-18]. The obtained results allow us to conclude that in the early stages of mineral deficiencies, the intensity of photosynthesis and production process is not limited by a slight decrease in capacity of the photosynthetic apparatus. Apparently, one of the main reasons for the growth retardation is less effective conversion of light energy into chemical energy during photosynthesis. The effective use of light and fertilizers is currently of great interest for breeding, and non-invasive optical tools that allow breeders to quickly and quantitatively evaluate these parameters are among the most promising technologies [15, 24, 25].

Photochemical reflection index PRI was developed to estimate the rate of change in the relative content of xanthophyll cycle pigments which are active regulators of light flux in pigment-protein complexes [20, 26, 27]. Transformation of the carotenoids of xanthophyll cycle, proceeding with the heat generation, reduces the excess of chlorophyll absorption by the antenna complex at high light intensity or under stress conditions. Thermal dissipation of superfluous energy is the most important function of carotenoids in photoprotection of the chloroplast photochemical system from irreversible damage by large energy inflow into the reaction centers that cannot be used. The change in PRI during plant growth can be the result of combination of the xanthophyll cycle activity and the change in the total pool of chlorophylls and carotenoids, which is a response to long-term plant acclimatization to habitat [28, 29]. The tendency to an increase in thermal dissipation (PRI_{mod}) in response to the ameliorant application is most manifested in Krasnoufimskaya 100 variety, especially with a lower nitrogen level (see Table 2). We did not find any significant deviation in the photochemical reflection index in Trizo plants. At a lower nitrogen supply, the ameliorant facilitates the conversion of carotenoids and thermal dissipation, which is particularly manifested in Krasnoufimskaya 100 variety.

The content of carotenoids was also assessed by SIPI (see Table 2). The SIPI value remained practically unchanged, reliable ($p \leq 0.05$) differences were found only between variants 1 and 3. G.A. Blackburn [26] showed a nonlinear relationship between the SIPI value and the carotenoids to chlorophyll ratio, which is best described by the logarithmic model ($R^2 = 0.86$). SIPI is not sensitive enough at low ratios, but becomes more sensitive when they increase. Apparently, it can explain the lack of reliable SIPI changes in response to the ameliorant and reduction in the nitrogen availability, since the chlorophyll content in all the test variants was quite high.

A reliable ($p \leq 0.05$) decrease in ARI_{mod} and FRI_{mod} indices occurs only at high nitrogen nutrition, both in Krasnoufimskaya 100 and Trizo varieties. Anthocyanins and flavonols basically absorb radiation in green and ultraviolet spectra, slightly absorb in the red and almost do not absorb in the blue. Anthocyanins accumulation at stress reduces the flux of photosynthetically active radiation that penetrates chloroplasts, thus promoting protection of reaction centers in plastids at stress emergence [22, 30, 31]. There are data that anthocyanins and flavonols also perform antioxidant functions, in particular chloroplast-located flavonoids remove singlet oxygen forming in plant tissues under the action of various stressful environmental factors [32].

The value of R_{800} primarily depends on the volume of intercellular air space, the mesophyll surface area to the leaf area ratio, as well as the internal structure of the leaf, the length of air-water boundary, size of cells and organelles [20]. Thus, an increase in R_{800} at mineral nutrition deficiency indicates a change in the inner structure of leaves, which promotes diffusion and a decrease in the absorbed solar radiation. Since the R_{800} value increases while the ameliorant introduction, it can be concluded that a decrease in soil acidity is accompanied by a change of leaf structure. Such changes in Krasnoufimskaya 100 variety occur when the ameliorant is introduced at nitrogen deficiency, whereas in Trizo variety at both high and low nitrogen levels in response to the ameliorant application at 1.0 H_h (see Table 2).

It was previously shown that one of the mechanisms of the nonspecific plant response to the stressful impact by downregulation of the photosystem II may be studied via changes of the reflection indices [16, 17]. Unlike the chlorophyll index the value of which characterizes the potential ability to absorb photosynthetically active radiation, all the other indices of Table 2 allow estimation of the absorbed light utilization efficiency. A slight decrease of this efficiency (with SIPI, R_{800}, PRI_{mod}, ARI_{mod} and FRI_{mod} increase) reflects inhibition of synthetic processes in the course of plants adaptation to the changing environmental conditions.

So, under good nitrogen supply (1 g/5 kg of soil), the grain weight in Leningradskaya 97 variety does not depend on the ameliorant application. In Krasnoufimskaya 100 there is a shift of positive response to the ameliorant towards lower doses, whereas Triso plants respond positively to all tested doses. The grain weight increase in these varieties at 0.25 H_h of the ameliorant is more than 30 and 17 %, respectively (for 0.50 and 0.75 H_h, the effect is also manifested, but 1.0 H_h reduces the grain yield of Krasnoufimskaya 100 plants). In the same varieties under different doses of the ameliorant the grain weight and the chlorophyll content in the leaves closely correlate ($R^2 = 0.87$ and $R^2 = 0.88$). The stimulating effect of the ameliorant is more pronounced at a lower dose of nitrogen (0.15 g/5 kg of soil). An increase in indices characterizing the efficiency of light energy conversion in photochemical processes (SIPI, R_{800}, PRI_{mod}, ARI_{mod} and FRI_{mod}) allows us to suggest that the ameliorant, by improving plant nutrition, promotes metabolism changes towards adaptation to environment conditions.

REFERENCES

1. Dobrovol'skii G.V., Shoba S.A., Balabko P.N. Pochvy i zemel'nye resursy Rossii. V knige: *Degradatsiya i okhrana pochv* /Pod redaktsiei G.V. Dobrovol'skogo [Soil degradation and preservation. G.V. Dobrovolskii (ed.)]. Moscow, 2002: 5-32 (in Russ.).
2. Nadezhkin S.M., Nadezhkina E.V. Vliyanie izvestkovaniya na gumusnoe sostoyanie pochv lesostepi Povolzh'ya. V sbornike: *Voprosy izvestkovaniya pochv* /Pod redaktsiei I.A. Shil'nikova, N.I. Akanovoi [Soil liming. I.A. Shilnikov, N.I. Akanova (eds.)]. Moscow, 2002: 119-125 (in Russ.).
3. Shil'nikov I.A., Sychev V.G., Akanova N.I., Zelenov N.A. V sbornike: *Sovremennye problemy i perspektivy izvestkovaniya kislykh pochv* [Relevant problems and prospects of liming acidic soils]. St. Petersburg, 2010: 19-24 (in Russ.).
4. Shil'nikov I.A., Sychev V.G., Akanova N.I. *Plodorodie*, 2013, 1(70): 9-14 (in Russ.).
5. Okorkov V.V. *Teoreticheskie osnovy khimicheskoi melioratsii kislykh pochv* [Theoretical aspects of chemical reclamation of acidic soils]. Vladimir, 2016 (in Russ.).
6. Yakushev V.P., Osipov A.I., Minnulin R.M., Voskresenskii S.V. *Agrofizika*, 2013, 2(10): 18-22 (in Russ.).
7. Nebol'sin A.N., Nebol'sina Z.P. *Teoreticheskie osnovy izvestkovaniya pochv* [Theoretical bases of soil liming]. St. Petersburg, 2005 (in Russ.).
8. Zelenov N.A., Shil'nikov I.A., Akanova N.I., Shvyrkov D.A. V sbornike: *Sovremennye problemy i perspektivy izvestkovaniya kislykh pochv* [Relevant problems and prospects of liming acidic

soils]. St. Petersburg, 2010: 30-34 (in Russ.).
9. Litvinovich A.V., Kovleva A.O., Pavlova O.Yu. *Agrokhimiya*, 2015, 5: 61-68 (in Russ.).
10. Neenan M. Adaptability of wheat varieties to acid soils. *Nature*, 1955, 175: 1090-1091 (doi: 10.1038/1751090b0).
11. Ataur Rahman M., Barma N.C.D., Sarker M.H., Sarker M.M.R., Nazrul M.M.I. Adaptability of wheat varieties in strongly acidic soils of Sylhet. *Bangladesh Journal of Agricultural Research*, 2013, 38(1): 97-104 (doi: 10.3329/bjar.v38i1.15194).
12. Tang C., Nuruzzaman M., Rengel Z. Screening wheat genotypes for tolerance of soil acidity. *Aust. J. Agr. Res.*, 2003, 54: 445-452 (doi: 10.1071/AR02116).
13. Litvinovich A.V., Kovleva A.O., Pavlova O.Yu. *Izvestiya Sankt-Peterburgskogo gosudarstvennogo agrarnogo universiteta*, 2013, 30: 59-64 (in Russ.).
14. Humplík J.F., Lazár D., Husičková A., Spíchal L. Automated phenotyping of plant shoots using imaging methods for analysis of plant stress responses — a review. *Plant Methods,* 2015, 11(29): 1-10 (doi: 10.1186/s13007-015-0072-8).
15. Ruckelshausen A., Busemeyer L. Toward digital and image-based phenotyping. In: *Phenomics in crop plants: trends, options and limitation.* J. Kumar, A. Pratap, S. Kumar (eds.). Springer, New Delhi, India, 2015: 41-60 (doi: 10.1007/978-81-322-2226-2).
16. Kanash E.V., Panova G.G., Blokhina S.Yu. Optical criteria for assessment of efficiency and adaptogenic characteristics of biologically active preparations. *Acta Horticulturae*, 2013, 1009: 37-44 (doi: 10.17660/ActaHortic.2013.1009.2).
17. Kanash E.V., Osipov Yu.A. Optical signals of oxidative stress in crops physiological state diagnostics. *Proc. 7th European Conference on Precision Agriculture (Wageningen, Netherlands*, 2009). E.J. van Henten, D. Goense, C. Lokhorst (eds.). Wageningen, 2009: 81-89 (doi: 10.3920/978-90-8686-664-9).
18. Yakushev V., Kanash E., Rusakov D., Blokhina S. Specific and non-specific changes in optical characteristics of spring wheat leaves under nitrogen and water deficiency. *Advances in Animal Biosciences,* 2017, 8(2), 229-232 (doi: 10.1017/S204047001700053X).
19. Yakushev V. P., Kanash E. V. Evaluation of wheat nitrogen status by colorimetric characteristics of crop canopy presented in digital images. *Journal of Agricultural Informatics*, 2016, 7 (1): 65-74 (doi: 10.17700/jai.2016.7.1.268).
20. Sims D.A., Gamon J.A. Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. *Remote Sens. Environ.*, 2002, 81(2-3): 337-354 (doi: 10.1016/S0034-4257(02)00010-X).
21. Pecuelas J., Barret F., Fitella I. Semi-empirical indices to assess carotenoids/chlorophyll a ratio from leaf spectral reflectance. *Photosynthetica*, 1995, 31(2): 221-230.
22. Merzlyak M.N., Gitel'son A.A., Chivkunova O.B., Solovchenko A.E., Pogosyan S.I. *Fiziologiya rastenii*, 2003, 50: 785-792 (doi: 10.1023/A:1025608728405) (in Russ.).
23. Merzlyak M.N., Solovchenko A.E., Smagin A.I., Gitelson A.A. Apple flavonols during fruit adaptation to solar radiation: spectral features and techniques for non-destructive assessment. *J. Plant Physiol.*, 2005, 162(2): 151-160 (doi: 10.1016/j.jplph.2004.07.002).
24. Gaju O., DeSilva J., Carvalho P., Hawkesford M.J., Griffiths S., Greenland A., Foulkes M.J. Leaf photosynthesis and associations with grain yield, biomass and nitrogen-use efficiency in landraces, synthetic-derived lines and cultivars in wheat. *Field Crops Research*, 2016, 193: 1-15 (doi: 10.1016/j.fcr.2016.04.018).
25. Araus J.L., Slafer G.A., Royo C., Serret D. Breeding for yield potential and stress adaptation in cereals. *Crit. Rev. Plant Sci.*, 2008, 27: 377-412 (doi: 10.1080/07352680802467736).
26. Blackburn G.A. Spectral indices for estimating photosynthetic pigment concentrations: a test using senescent tree leaves. *International Journal of Remote Sensing*, 1998, 19: 657-675 (doi: 10.1080/014311698215919).
27. Gamon J.A., Serrano L., Surfus J.S. The photochemical reflectance index: an optical indicator of photosynthetic radiation use efficiency across species, functional types, and nutrient levels. *Oecologia*, 1997, 112: 492-501 (doi: 10.1007/s004420050337).
28. Gitelson A.A., Gamon J.A., Solovchenko A. Multiple drivers of seasonal change in PRI: Implications for photosynthesis 1. Leaf level. *Remote Sens. Environ.*, 2017, 191: 110-116 (doi: 10.1016/j.rse.2016.12.014).
29. Gitelson A.A., Gamon J.A., Solovchenko A. Multiple drivers of seasonal change in PRI: Implications for photosynthesis 2. Stand level. *Remote Sens. Environ.*, 2017, 190: 198-206 (doi: 10.1016/j.rse.2016.12.015).
30. Hatier J.-H.B, Gould K.S. Anthocyanin function in vegetative organs. In: *Anthocyanins.* C. Winefield, K. Davies, K. Gould (eds.). Springer, NY, 2008: 1-19 (doi: 10.1007/978-0-387-77335-3_1).
31. Steyn W.J., Wand S.J.E, Holcroft D.M., Jacobs G. Anthocyanins in vegetative tissues: a proposed united function in photoprotection. *New Phytol.*, 2002, 155: 349-361 (doi: 10.1046/j.1469-8137.2002.00482.x).
32. Agati G., Matteini P., Goti A., Tattini M. Chloroplast-located flavonoids can scavenge singlet oxygen. *New Phytologist,* 2007, 174: 77-89 (doi: 10.1111/j.1469-8137.2007.01986.x).