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Temperature: influence on photosynthesis and crop yield

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A RELATIONSHIP BETWEEN CHLOROPHYLL PHOTOSYNTHETIC POTENTIAL AND YIELD OF WINTER WHEAT (*Triticum aestivum* L.) AT ELEVATED TEMPERATURES

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Abstract

Development of the indices for selection of high-yielding crops and the models, forecasting crop yields, necessitate the analysis of the relationship between photosynthetic traits and productivity. Chlorophyll photosynthetic potential, characterizing the total amount of chlorophyll in the above-ground parts of plants (or in leaves) per unit of ground surface area during the growing season or a certain period, under optimal weather conditions correlated most closely with yield (T.M. Shadchina et al., 2007; E. Kutasy et al., 2005). Modern global climate change may primarily affect the heat-sensitive crops in particular winter wheat causing disruption in the relationship between photosynthetic traits and productivity. In field experiment, we examined the effects of increased air temperatures during the spring—summer growing season on indices of photosynthetic apparatus in the high-yielding varieties of common winter wheat Smuhlyanka and Pereyaslavka on the different levels of mineral nutrition (without fertilizers and fertilizing in the fall and at different phases of the spring—summer vegetation in doses $N_{90}P_{60}K_{60}S_{10}$ and $N_{120}P_{90}K_{90}S_{20}$). Investigations were carried out in 2009 and 2011 with elevated air temperatures during the growing season at the experimental agricultural station of the Institute of Plant Physiology and Genetics, National Academy of Sciences of Ukraine (Kiev region). It was shown that such weather conditions led to a decrease in the chlorophyll content in the leaves, the size of crop surface and the duration of its operation, as well as grain yield. In all cases (both at high level of mineral nutrition and without fertilizers) leaf surface area in 2009 was higher than under the corresponding treatments in 2011 at all studied vegetation phases. Mineral fertilizers increased the leaf area index in both years by average 1.5-2.0 times (in Pereyaslavka at milk-wax ripeness phase it increased almost 5 times if compared to the control). Chlorophyll content in leaves of both varieties depended on year: it was 5.5-6.0 and 3.5-4.5 mg/dm^2, respectively, in 2009 and 2011 if fertilizers were used, and 3.2-4.3 and 2.8 mg/dm^2, respectively, in the control. In most cases, the maximum values of the pigments content in the averaged sample of all green leaves from plant were observed in the phase of milk ripeness, probably, due to the complete withering away of leaves of lower layers. Mineral fertilizers increased the amount of chlorophyll in the leaves of both varieties. According to the results of dispersion analysis (*F*-Fisher test), the greatest influence on changes in the indices of the photosynthetic capacity in our experiments have the conditions of the year, the second most important factor was the level of mineral nutrition. The value of chlorophyll photosynthetic potential was more dependent on a combination of factors «variety × year conditions» and less on the interaction of the factors «year conditions × mineral nutrition level» and «variety × mineral nutrition level». High and similar correlation coefficient values (0.93 to 0.99) between grain yield and chlorophyll photosynthetic potential were observed for data sets within single year, variety or mineral nutrition treatment, a strong positive dependence revealed for the combined data sets for both years. The data have shown that the close correlation between the leaf chlorophyll photosynthetic potential and yield of winter wheat is retained in the conditions of air high temperature and this dependence can be described by the same regression equation for any varying factors.

Keywords: *Triticum aestivum* L., grain yield, leaf area index, chlorophyll, chlorophyll photosynthetic potential of leaves.

The analysis of the relationship between photosynthetic traits and productivity is essential for understanding regularities and patterns of yield formation with a view to further development of the breeding criteria of high-yielding crops and the models to forecast the crop yields. According to data reported, chlorophyll photosynthetic potential (ChPhP), which characterizes the total amount of chlorophyll in the above-ground parts of plants (or in leaves) per unit of ground surface area during the growing season or a certain period, is most closely related to crop yield (1-3). In different winter wheat genotypes we have found a close correlation between ChPhP in leaves and crop productivity allowing forecasting the yield magnitude (4). High correlation between ChPhP and crop yield is due to the representativeness of the ChPhP as a parameter reflecting both dynamics of biomass production and the effect of absorbed photosynthetically active radiation (PAR) in crops during vegetation (5-7).

In cereals the high correlation between ChPhP and productivity is usually obseved in the years when the weather conditions are optimal (4, 8, 9). It is considered that the high leaf area and leaf chlorophyll indexes in crops, especially at high doses of nitrogen fertilizes, could be counterproductive because of more losses of soil moisture and more consumption of assimilated carbon for the respiration under water deficit and high temperatures (10). Due to global climate changes a frequency and duration of periods with higher temperatures increased significantly (11, 12), and in Ukraine from 2007 to 2012, the record maximum daily temperatures during the spring-summer growing season were not registered in 2008 only.

Common winter wheat (*Triticum aestivum* L.) is heat sensitive, and the highest yield losses are caused by the impact of high temperature during the reproductive phase (13-15). High temperature stress inhibits chlorophyll synthesis and photosynthetic activity, accelerates leaf aging, decreases leaf life span, oppresses and interferes with the formation of the elements of the ear and the pollen fertility, suppresses seeds formation and filling, ultimately causing a decrease in the number and weight of grains per ear (16, 17). It is still unclear whether the changes in reproductive processes affect yield production alone or they are related to deficit of photoassimilates (14, 18), nevertheless, an increase in temperature during wheat vegetation evidently causes a disruption in the relationship between photosynthetic traits and productivity. Therefore, in the years with extremely high temperatures the use of the relationship between photosynthetic parameters and productivity for breeding and the crop yield forecasting could be problematic.

In this study we examined a relationship between the performance of photosynthetic apparatus and grain productivity in winter wheat crops at different levels of mineral nutrition in the years with temperature excesses during plant vegetation.

Methods. Investigations were carried out in 2009 and 2011 with elevated air temperatures during the growing season at the experimental agricultural station of the Institute of Plant Physiology and Genetics, National Academy of Sciences of Ukraine (Kiev region). Two high-yielding varieties of common winter wheat, Smuhlyanka and Pereyaslavka, were estimated. Smuhlyanka is a early to middle ripening variety with 278-281 day vegetation period and the crop yield ranging from 6,0 to 11,5 t/ha, and Pereyaslavka is a middle ripening variety with 280-287 day vegetation period and the crop yield ranging from 6,0 to 10,3 t/ha (19). A sowing rate was 5.0-5.5 million per ha. The shoot number at harvesting varied from 500 to 750 per m^2. A plot size was 40 m^2 at a 4-fold repetition, and 20 plants from each plot were analyzed. Experiments were carried out on the sod slightly to medium podzolized gleyed sandy soils with 1.8 % humus and pH (KCl) 6.2. Mineral fertilizers ($N_{90}P_{60}K_{60}S_{10}$ and $N_{120}P_{90}K_{90}S_{20}$) were used in autumn and in certain phases of plant growth in spring and summer. In control no fertilizers were used.

To determine the content of photosynthetic pigments and assimilation surface area in crops the samples were collected during the period of flowering to milky-wax ripeness. Chlorophyll content in average probe of all leaves from a shoot was determined spectrophotometrically after dimethylsulfoxide (DMSO) extraction (20). Green leaves area per shoot was calculated as their length multiplied by the maximum width with a correction factor 0.76, and the obtained value multiplied by shoot density was taken as the leaf area index (LAI). Chlorophyll index (ChI) was calculated as LAI multiplied by chlorophyll content in leaves. ChPhP was determined by summarizing daily CHIs for certain period (21). For its calculation the graphs of chlorophyll indexes in green leaves for the time from flowering to milky-wax ripeness phase were plotted.

Experimental data were statistically processed using Microsoft Excel.

Results. Both in 2009 and 2011 an average temperature during the reproductive development of winter wheat plants was significantly higher than historical averages. In 2009 daily average temperatures exceeded the climatic norm by 0.8 °C for 2 weeks from plant earing to flowering and then by 1.5 °C from milk ripeness (MR) to milk-wax ripeness (MWR) phase. From flowering to MWR the difference was 1.2 °C on average. In 2011 an average temperatures exceeded significantly, by 5.1 °C, the climatic norm for all time from flowering to MWR, moreover, in some days it was more than 8 °C higher. Besides, in 2011 thermal abnormalities occurred 1.5 week prior to flowering and coincided with the lack of rainfall. Hydrothermal coefficient in Mays 2009 and 2011 was 0.8 and 0.6, respectively, while its long-term average value for the Kiev region in May is 1.2.

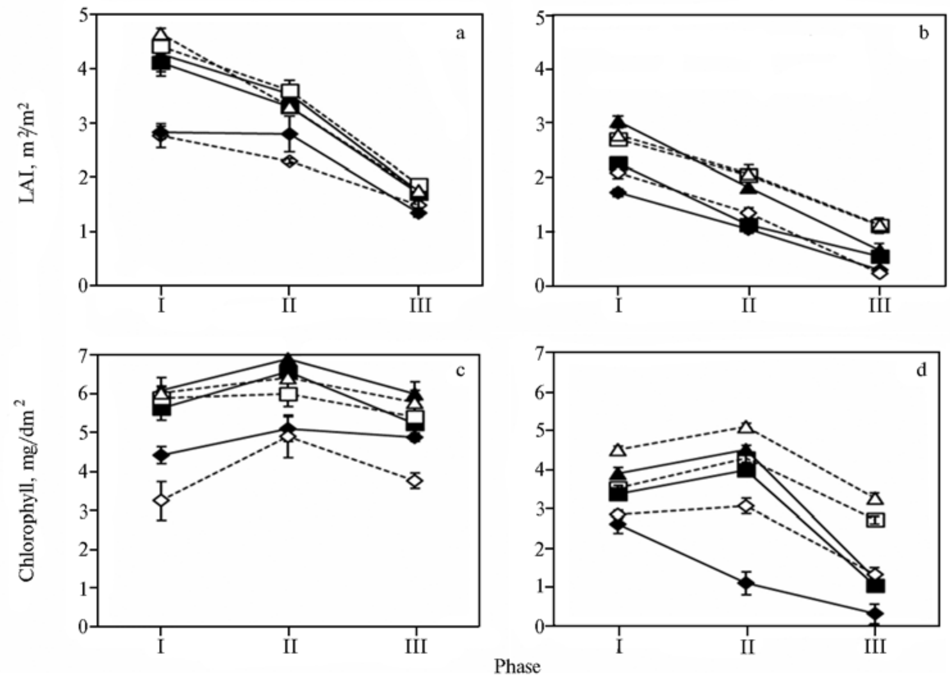

Fig. 1. Dynamics of leaf area index (LAI) **of crops** (a, b) **and chlorophyll content** (c, d) **in the years with high air temperature during vegetation** (a, c — 2009, b, d — 2011) **in common winter wheat** (full line referred to Smuhlyanka variety, dotted line referred to Pereyaslavka variety) **from flowering** (I) **to milk-wax ripeness** (III) **at different levels of mineral nutrition:** —◆— and ··◇·· — control; —■— и ··□·· — $N_{90}P_{60}K_{60}S_{10}$; —▲— и ··△·· — $N_{120}P_{90}K_{90}S_{20}$ (experimental agricultural station of the Institute of Plant Physiology and Genetics, National Academy of Sciences of Ukraine, Kiev region).

These weather conditions significantly affect plant development. In 2011 the flowering occurred 12 days earlier compared to 2009, while the time from flowering to MWR differed slightly, being about 4 days less in 2009.

Weather conditions influenced considerably the assimilation apparatus of crops and LAI values during wheat vegetation (Fig. 1). In all cases (both at high level of mineral nutrition and without fertilizers) leaf surface area in 2009 was higher than under the corresponding treatments in 2011 at all studied vegetation phases. Mineral fertilizers increased 1.5-2.0 times the leaf area index in both years, while in the Pereyaslavka plants at milk-wax ripeness phase the leaf area index was almost 5 times as much as in the control.

Chlorophyll content in leaves of both varieties depended on year, being in 2011 lower that in 2009. It was 5.5-6.0 and 3.5-4.5 mg/dm^2, respectively, in 2009 and 2011 if fertilizers were used, and 3.2-4.3 and 2.8 mg/dm^2, respectively, in the control (see Fig. 1). Similar patterns were observed for next two phases. However, in 2011 a reduction in chlorophyll content was more severe, being particularly noticeable in Smuhlyanka plants, especially under deficit of mineral nutrients, probably due to acceleration of the leaf aging and the nitrogen reutilization induced by elevated temperatures. In Pereyaslavka plants the chlorophyll content was less influenced by weather during vegetation, and in warmer 2011 this parameter was in general higher compared to Smuhlyanka plants.

Mineral fertilizer increased chlorophyll content in leaves of both varieties. In 2009 and 2011 it was 1.3-1.5 and 1.7-2.2 times higher, respectively, if compared to control. As the dose of fertilizer increased, the level of photosynthetic pigments in plants reliably went up in both varieties.

It should be noted that in most cases the maximum values of the pigments content in the averaged sample of all green leaves from a plant were observed during the phase of milk ripeness, probably due to the complete withering away of leaves of lower layers.

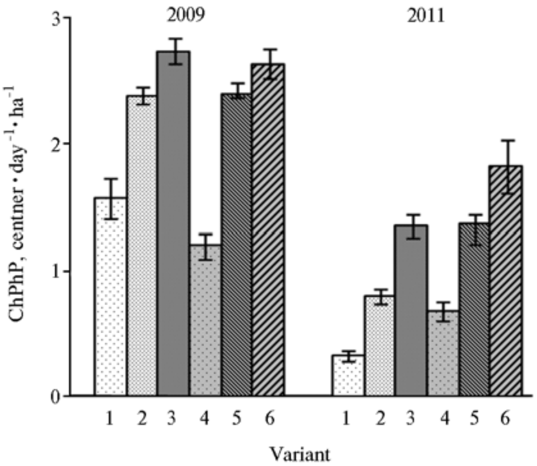

Fig. 2. Chlorophyll photosynthetic potential (ChPhP) **in common winter wheat** (1-3 — Smuhlyanka variety, 4-6 — Pereyaslavka variety) **from flowering to milk-wax ripeness at different levels of mineral nutrition in the years with high air temperature during vegetation**: 1 and 4 — control, 2 and 5 — $N_{90}P_{60}K_{60}S_{10}$, 3 and 6 — $N_{120}P_{90}K_{90}S_{20}$ (experimental agricultural station of the Institute of Plant Physiology and Genetics, National Academy of Sciences of Ukraine, Kyiv region).

In Pereyaslavka plants the changes in chlorophyll content during ontogenesis were similar for both years and did not depend of the mineral nutrition level, thus providing in late ontogenesis approximately the same relative differences when the fertilizers were or were not used. In Smuhlyanka plants the most influence of the fertilizers were detected at MR, in 2011 especially, and at MWR phase the differences decreased due to rapid reduction of chlorophyll content under fertilization.

ChPhP as an integrated crop index reflecting plant assimilation area, chlorophyll content and the changes in two these parameters during ontogenesis (Fig. 2) in 2011 were much lower if compared to 2009. Nevertheless, the effect of weather conditions differed for the varieties and depended on mineral nutrition. In 2009 as compared to 2011 Smuhlyanka plants had the ChPhP value 4.8 times higher in control, and 3.0 and 2.0 times higher at $N_{90}P_{60}K_{60}S_{10}$ and $N_{120}P_{90}K_{90}S_{20}$, respectively. In Pereyaslavka plants the differences were significantly less, being 1.8-fold in control and 1.5-fold at $N_{120}P_{90}K_{90}S_{20}$. In turn, the influence of fertilizers on the ChPhP also depended on the varietal specificity and the year conditions. In 2009 fertilizers effects were less and similar, i.e. 1.7-fold and 2.2-fold for Smuhlyanka and Pereyaslavka varieties, respectively. In 2011 fertilizing $N_{120}P_{90}K_{90}S_{20}$ increased ChPhP 4.0 times and 2.5 times in Smuhlyanka and Pereyaslavka varieties, respectively.

1. Estimation of factors affecting variations of photosynthetic parameters in Smuhlyanka and Pereyaslavka common winter wheat varieties (Fisher *F*-test; experimental agricultural station of the Institute of Plant Physiology and Genetics, National Academy of Sciences of Ukraine, Kyiv region)

Factors and their combination	F_{actual}				$F_{calculated}$	
	chlorophyll index			ChPhP		
	flowering	MR	MWR		05	01
Year (a)	374	633	431	3913	4.84	9.85
Variety (b)	2.30	1.08	6.84	54.30		
Mineral nutrition (c)	123	103	30.1	1516	3.98	7.20
ab	0.40	28.40	7.30	264	4.84	9.85
ac	28.00	8.53	3.73	46.80		
bc	2.57	2.47	3.61	33.10	3.98	7.20
abc	1.28	0.13	0.42	2.57		

C o m m e n t s. ChPhP — chlorophyll photosynthetic potential of leaves, MR and MWR — milk ripeness and milk-wax ripeness, respectively.

2. Grain yield (centner/ha) **in Smuhlyanka and Pereyaslavka common winter wheat varieties at different levels of mineral nutrition in the years with high air temperature during vegetation** ($X \pm x$; experimental agricultural station of the Institute of Plant Physiology and Genetics, National Academy of Sciences of Ukraine, Kiev region

Variant	Smuhlyanka		Pereyaslavka	
	2009	2011	2009	2011
Control	60.0±3.1	27.7±1.9	55.1±2.6	24.5±1.4
$N_{90}P_{60}K_{60}S_{10}$	102.3±2.9	39.6±4.5	98.4±2.7	53.0±3.8
$N_{120}P_{90}K_{90}S_{20}$	105.8±2.6	45.3±5.6	99.0±3.8	56.4±2.8

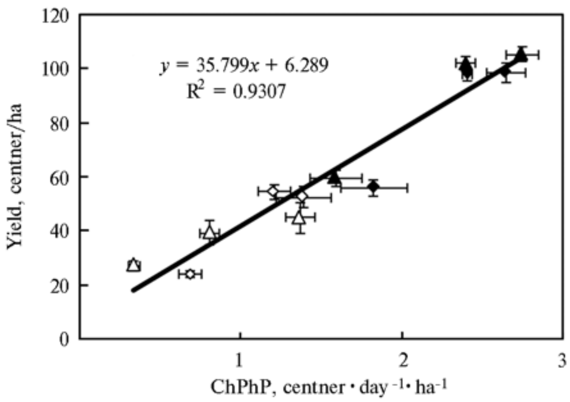

Fig. 3. Crop yield and chlorophyll photosynthetic potential (ChPhP) **in common winter wheat varieties in the years with high air temperature during vegetation: ▲, ∆ —** Smuhlyanka variety, 2009 and 2011, respectively; ♦, ◊ — Pereyaslavka variety, 2009 and 2011, respectively (experimental agricultural station of the Institute of Plant Physiology and Genetics, National Academy of Sciences of Ukraine, Kiev region).

According to dispersion analysis, in our experiments the ChI and ChPhP values were mostly influenced by the year conditions (Table 1). Mineral nutrition was the second factor affecting variation of these indexes, and the least effect was found for genotype. Nevertheless, ChPhP was much dependent on combination «variety × year conditions», while the influence in combinations «year conditions × mineral nutrition» and «variety × mineral nutrition» was lower.

In plants of two investigated varieties grain productivity changed together with the photosynthetic traits. In unfavorable 2011 as compared to 2009 the crop yield decreased sharply (Table 2). In Pereyaslavka and Smuhlyanka plants grain productivity decreased 1.8-2.2 times and 2.0-2.5 times, respectively, depending on the level of mineral nutrition.

In a pooled data set for both years a close positive relationship between the crop grain productivity and the ChPhP during the period from flowering to milk-wax ripeness was confirmed by correlation analysis (Fig. 3). It should also be noted that the high and close *r* values (0.93-0.99) were found for the data sets for each year, each variety or each level of mineral nutrition.

Thus, the data herein confirm that in winter wheat under air high temperature the correlation between the leaf chlorophyll photosynthetic potential (ChPhP) as integrated parameter of photosynthetic capacity of plants and the crop yield remains close. This dependence can be described by the same regression equation for any varying factors, meaning year conditions, mineral nutrition level and the variety genotype. As the temperature during plant growth and reproductive development increases, the assimilation area, chlorophyll content and leaf life span decrease resulting in decline of crop yield. For both varieties, an increase in assimilation area and chlorophyll content due to higher mineral nutrition leads to a corresponding yield raise both at moderate and drastic temperature rise, despite a considerably different sensitiveness of the varieties to the growth conditions. At a high level of mineral nutrients the productivity of winter wheat crops is higher, probably due to higher chlorophyll content in leaves and a longer period during which the leaf index in crops remains optimal.

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