UDC (581.132 + 128:631.84 : 58.032.3) : 633.11

INFLUENCE OF ABIOTIC FACTORS ON PHOTOSYNTHESIS AND PRODUCTION PROCESS OF DIFFERENT WINTER WHEAT VARIETIES

B.I. Guliaev [1], H.B. Huliaieva [2], V.F. Patyka [2]

[1] *Institute of Plant Physiology and Genetics, NAS of Ukraine*
31/17, Vasylkivska Str., Kyiv, Ukraine, 03022
[2] *D.K. Zabolotny Institute of Microbiology and Virology, NAS of Ukraine*
154, Acad. Zabolotnoho Str., Kyiv, Ukraine, 03680

E-mail: patykavolodymyr@gmail.com, ab_k@ukr.net

Received on January 26, 2017

Aim. The investigation of photosynthesis and production process in winter wheat varieties, different in their grain productivity, its connection to the active surface area of the root system in optimal conditions, under drought and mineral nutrition deficiency. **Methods.** Physiological, biochemical, gas exchange analysis, statistical methods. **Results.** It was demonstrated that different conditions of mineral nutrition and soil drought have impact on the intensity of photosynthesis, photo- and dark respiration, the content of pigments in the flag leaf of winter wheat plants; the results obtained testify to the interrelation of these indices to the active surface area of the root system and grain productivity of winter wheat varieties, different in potential grain productivity. **Conclusions.** It was determined that under drought the photosynthetic apparatus of a highly productive winter wheat variety Smuhlianka demonstrated higher stability compared to the photosynthetic apparatus of the variety Myronivska 808, moderately resistant to drought conditions. At the same time, highly intensive varieties of winter wheat, Favorytka and Smuhlianka, had a larger active surface area of the root system and chlorophyll content in leaves, compared to Myronivska 808 plants, notable for their lower grain productivity. It was determined that there was considerable reliable correlation between the intensity of flag leaf photorespiration and the active surface area of the root system in winter wheat plants of varieties Myronivska 808 and Smuhlianka ($r = 0.805$). Considerable correlation ($r = 0.878$) was found between the intensity of flag leaf photorespiration in the heading-blossoming phase and the sum of chlorophylls in these leaves. It was determined that the index $S_{r\ act} \times$ chlorophyll may be used to estimate the active surface area of the root system with the error of up to 3.8 % for five winter wheat varieties.

Keywords: *Triticum aestivum* L., photosynthesis, photorespiration, active surface area of the root system, chlorophyll, productivity.

DOI: 10.15407/agrisp4.01.056

INTRODUCTION

One of the crucial factors, defining the efficiency of the photosynthetic assimilation, is temperature, which is especially relevant due to global changes of the climate. In recent decades, rapid and unpredictable changes in weather conditions have been remarkable for considerable deviations of mean temperatures during as few as two current months from the norm. For instance, according to the experts' data, the losses of the yield of agricultural crops due to unfavorable weather conditions fluctuate in the range of 10–30 %, and for some plants they may amount to 50 % and more. Therefore, the cultivation of selective varieties with high productivity potential, the technology of processing which has been adjusted to specific agroclimatic conditions, is related to the complexities, caused by climate changes, which may be one of the factors, inhibiting the realization of productive possibilities of these varieties [4, 7] 1, 2 [1–5].

It is known that 90–95 % of the organic mass of plants is formed during the process of photosynthesis, so abiotic stresses, reducing its efficiency, in particular, drought, promote a considerable reduction of crop yield [6]. It was determined that even a slight reduction in soil humidity prior to the occurrence of evident changes in water supply for leaves reduces the photosynthetic consumption of carbon dioxide [5, 7]. The inhibition of photosynthesis under moderate and short drought is caused, first of all, by partial closure of stomatoes. Long-term and deeper water deprivation of photosynthesizing tissues results in considerable changes in photosynthetic metabolism and so called non-stomatal limitation of photosynthesis. It was experimentally proven that in these conditions there is a reduction in the activity of photosystems I and II and photophosphorylation, as well as a decrease in the activity and content of ribulose biphosphate carboxylase (RBPC) [7, 8].

The release of carbon dioxide and its loss in the photorespiration process amount to 50 % from the visible photosynthesis of the leaf. Though the issue of the physiological role of this process is yet to be studied in fine detail, there are some assumptions in the scientific literature concerning a relevant role of glycolate metabolism in the regulation of photosynthetic assimilation of CO_2 in stressful conditions [8]. It is known that under light the leaves of C-3-plants have the simultaneous processes of photosynthetic consumption of carbon dioxide and its release during photorespiration, and the intensity of the latter may amount to 50 % of the intensity of visible photosynthesis. When photorespiration was discovered, there was an assumption that this process decreased photosynthesis efficiency, due to which the obtaining of genotypes of C-3-plants with a low level of the photorespiration of leaves, using the methods of selective genetics, would allow getting a considerable increase in the productivity potential for these varieties of plants. However, further studies revealed that during the photosynthesis inhibition with the assimilates of wheat plants, the intensity of photorespiration promoted the preservation of the activity of photosynthetic apparatus due to the changes in glycolate metabolism, which enhanced the decarboxylation of its intermediates, not changing the ratio of its metabolism flows [9].

Numerous studies of the “green revolution” period investigated the connection between grain productivity and the development of the photosynthetic apparatus of winter wheat plants and revealed close correlation between grain productivity, photosynthetic potential of the sprout and chlorophyll photosynthetic potential. There were rather detailed studies of the specificities of the root system and its relation to grain productivity of plants and resistance to abiotic factors. However, little attention was paid to the investigation of the functional activity of the root system as well as of its absorbing part – root fibrillas, the most active part of the root during the consumption of nutrients [10–14]. The role of fibrillas is known for both the consumption and release of substances, namely cytokinins, into the rhizosphere, where they fulfill the functions of growth stimulators and play an important role in maintaining resistance to stress factors [15]. The analysis of the abovementioned led us to the decision to investigate the active surface of the root system and its interrelation with photorespiration and grain productivity. It was based on the assumption that the most adequate parameter, related to the functional activity of the root system, is the zone of root fibrillas, which was defined by us as the active surface area of the roots. Thus, the activity of the root fibrillas during the consumption of water and mineral elements from soil is several orders higher compared to the core part of the root, and their mass is several orders smaller [11, 12].

Therefore, the aim of this work was to study the intensity of photosynthesis, photorespiration and the content of pigments in the flag leaf of winter wheat depending on the surface area of the plant roots and grain productivity of different varieties of winter wheat, using the conditions of greenhouse experiments.

MATERIALS AND METHODS

A series of greenhouse experiments (2011–2012) was used to investigate the intensity of flag leaf photorespiration during the heading-blossoming phase with the active surface area of the winter wheat plant roots of varieties, different in their grain productivity, as well as to reveal the connection between the chlorophyll content in the flag leaf and photorespiration intensity.

The object of the study: winter wheat plants of the varieties Myronivska 808, Smuhlianka, Poliska 90 and Volodarka. The experiments were conducted in the greenhouse in the territory of the Institute of Plant Physiology and Genetics, NAS of Ukraine.

The plants were grown in Wagner pots on 8 kg of gray podzolized soil. The experiments were repeated four times.

Greenhouse experiment 2011. $N_{90}P_{90}K_{90}$ was introduced into soil prior to sowing. Variants: 1) soil drought at 30 % of maximum water capacity (MWC) during the heading-blossoming phase, which was created by terminating the irrigation with its subsequent restoration after 6 days; 2) decrease in soil humidity down to 30 % of MWC with its subsequent irrigation restoration during the phases of stem elongation and heading-blossoming. The content of water in tissues and soil humidity in vessels were measured by the weight method. Water deficiency was determined while comparing water content in the vegetative tissue against its content in the same tissue in the state of complete water saturation – in the turgor state.

Greenhouse experiment 2012. Variants: 1) optimal mineral nutrition ($N_{90}P_{90}K_{90}$); 2) mineral nutrition deficiency ($N_{20}P_{20}K_{20}$).

The exchange of CO_2 of plants was measured using the infrared gas analyzer OA-5501 at the temperature of 25 ºC and the intensity of photosynthetically active radiation (PAR) of 400 W/sq.m. [16]. Photorespiration intensity was estimated by the level of CO_2 release during the first 60 s after switching off the light. Gas exchange indices were determined using the standard method [17]; chlorophyll content – by the method of extraction in DMSO [18]; the areas of total and active surface of the roots – by Kolossov's method [11]. The statistical processing of the obtained results was conducted using Statistica 8.0 and other software (Microsoft Excel).

RESULTS AND DISCUSSION

It was determined that there were differences in the impact of drought on the photosynthetic apparatus of winter wheat varieties, different in their drought resistance: Myronivska 808 (moderately drought-resistant variety) and highly intensive variety Smuhlianka (drought-resistant, winter-hardy variety, resistant to diseases). According to our data, the decrease in soil humidity down to 30 % of MWC led to a considerable increase in water deficiency of leaves (phase of 2–4 leaves) in both varieties. Soil drought in the heading-blossoming phase led to the considerable inhibition of photosynthetic apparatus activity with a simultaneous decrease in chlorophyll content in the flag leaves of winter wheat variety Myronivska 808 1.3 times and that of Smuhlianka variety – 1.2 times (Table 1). The estimation of the intensity of assimilation processes for CO_2 under drought demonstrated the decrease in the intensity of photosynthesis, photorespiration, transpiration, as well as the increase in dark respiration with simultaneous increase in the resistance to diffusion for both Myronivska 808 and Smuhlianka, compared to the control. According to the data of Table 1, the intensity of photosynthesis of winter wheat plants of Myronivska 808 and Smuhlianka varieties decreased 4 and 3.6 times respectively, and that of photorespiration – 1.2 and 1.6 times. On the contrary, dark respiration increased 1.3- and 1.1-fold with the decrease in transpiration intensity 5 and 3.6 times respectively.

It is known that the increase of leaf resistance shortens water loss and is a relevant factor of the adaptation of leaves to drought. The study demonstrated the differences in these indices between moderately drought-resistant variety Myronivska 808 and more drought-resistant variety Smuhlianka. It was established that under drought the indices of total and leaf resistance of CO_2 diffusion increased for a less drought-resistant variety Myronivska 808 (4.3 and 5.7 times) compared to Smuhlianka variety (3.8 and 4.0 times).

Table 1. The indices of gas exchange of CO_2 of the flag leaf of different varieties of winter wheat (heading-blossoming phase)

Variant	Photosynthesis intensity	Photorespiration	Dark respiration, mg CO_2/(sq.dm · h)	Transpiration, g H_2O/(sq.dm · h)	Total resistance to diffusion	Leaf resistance to diffusion	Mesophyll resistance to diffusion, s/cm
Myronivska 808 variety							
Control (C)	30.1 ± 0.6	5.5 ± 0.17	1.5 ± 0.05	2.70 ± 0.08	7.36 ± 0.22	3.88 ± 0.12	3.49 ± 0.10
Drought (D)	7.5 ± 0.15	4.5 ± 0.13	2.0 ± 0.07	0.54 ± 0.02	31.4 ± 0.9	22.2 ± 0.70	9.19 ± 0.28
D/C	0.25 ± 0.01	0.82 ± 0.02	1.33 ± 0.04	0.20 ± 0.01	4.27 ± 0.13	5.74 ± 0.17	2.63 ± 0.08
Smuhlianka variety							
Control (C)	30.0 ± 0.9	9.4 ± 0.3	1.9 ± 0.1	2.48 ± 0.07	7.39 ± 0.22	4.28 ± 0.13	3.11 ± 0.09
Drought (D)	8.3 ± 0.25	6.0 ± 0.19	2.0 ± 0.1	0.69 ± 0.02	28.31 ± 0.85	17.22 ± 0.52	11.09 ± 0.33
D/C	0.44 ± 0.01	0.64 ± 0.20	1.05 ± 0.03	0.28 ± 0.01	3.83 ± 0.03	4.02 ± 0.12	3.56 ± 0.11

Mesophyll resistance, on the contrary, in a more drought-resistant variety Smuhlianka increased 3.6 times, and in variety Myronivska 808 – 2.6 times (Table 1). It was determined that there were specific changes in the ratio of indices of gas exchange of CO_2 (Table 2), which testifies to a higher increase in the share of photo- and dark respiration under drought in a less drought-resistant variety Myronivska 808.

It was determined in our previous work, investigating the area of total and active surface area and root provision of different varieties of winter wheat, including the abovementioned ones, that the root provision for the leading sprout of Smuhlianka plants was higher than that for Myronivska 808 (1.50 compared to 1.16 sq.cm/sq.cm). Thus, it was demonstrated that winter wheat varieties with higher grain productivity were remarkable for a larger area of active surface area of the roots, longer lifetime of the leaf apparatus and had higher content of pigments – chlorophylls and carotinoids – in the leaves, which conditioned higher photosynthetic potential of these varieties during the reproductive period [11]. We also assumed that varieties with better root provision were more stable to the impact of abiotic factors, including water shortage.

The investigations of the interrelation between the indices of productivity and photorespiration in optimal conditions of mineral nutrition (Table 3) demonstrated higher intensity of photorespiration for Smuhlianka, a more stable winter wheat variety, remarkable for higher grain productivity.

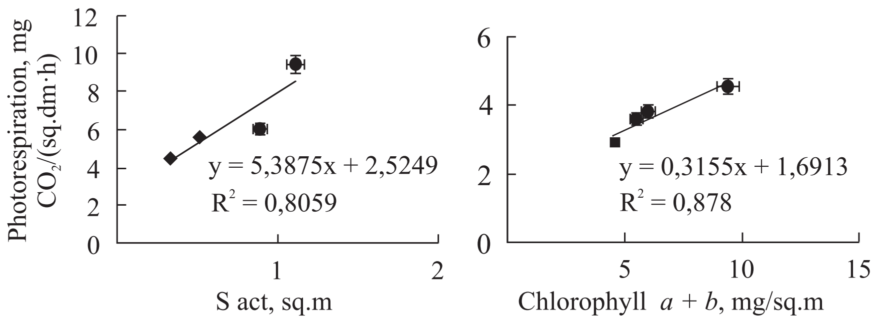
Therefore, while in optimal conditions there was higher total rate of photorespiration of winter wheat

Table 2. The ratio of gas exchange indices of CO_2 of the flag leaf of winter wheat of varieties Myronivska 808 and Smuhlianka (the heading-blossoming phase)

Variant	Photorespiration/Photosynthesis intensity	Dark respiration (mg CO_2/(sq.dm · h)/Photosynthesis intensity	Photorespiration/Dark respiration	Total chlorophyll content ($a + b$) in the flag leaf, mg/dm³	Active surface area of the root	Photorespiration	Photorespiration/Active surface area of the root	Photorespiration/Total chlorophyll content ($a + b$) in the flag leaf, mg/dm³
Myronivska 808								
Control	0.18 ± 0.01	0.05 ± 0.002	3.60 ± 0.10	3.60 ± 0.10	0.51 ± 0.02	5.5 ± 0.2	10.8 ± 0.3	1.50 ± 0.04
Drought	0.60 ± 0.02	0.27 ± 0.001	3.75 ± 0.10	2.81 ± 0.10	0.33 ± 0.01	4.5 ± 0.1	13.6 ± 0.4	1.96 ± 0.1
Smuhlianka								
Control	0.31 ± 0.01	0.06 ± 0.002	4.94 ± 0.1	4.55 ± 0.14	1.11 ± 0.03	9.4 ± 0.25	8.5 ± 0.26	2.06 ± 0.06
Drought	0.72 ± 0.02	0.33 ± 0.01	3.00 ± 0.1	3.82 ± 0.11	0.89 ± 0.03	6.0 ± 0.18	6.7 ± 0.2	1.57 ± 0.05

Table 3. The interrelation of the indices of grain productivity and photorespiration of the flag leaf of winter wheat plants of varieties Myronivska 808 and Smuhlianka (the heading-blossoming phase)

Photorespiration of the flag leaf, mg CO_2/(sq.dm · h)	The mass of grain of the head of the leading sprout, g	The mass of grain of the head of the leading sprout/Photorespiration of the flag leaf	The mass of 1000 grains, g	The mass of 1000 grains/Photorespiration of the flag leaf
Myronivska 808				
5.5 ± 0.11	1.11 ± 0.02	0.200 ± 0.01	41.8 ± 1.3	7.6 ± 0.2
Smuhlianka				
9.4 ± 0.20	1.48 ± 0.04	0.156 ± 0.003	47.3 ± 1.4	5.0 ± 0.1



The dependence of photorespiration intensity of the flag leaf (the heading-blossoming phase) on the active surface area of plant roots (*a*) and the chlorophyll content a + *b* (*b*) of varieties Myronivska 808 and Smuhlianka

plants of Smuhlianka variety, under such stress factors as drought the increase in this index was not so significant as for Myronivska, a less stable variety.

At the same time, the experiments with plants of winter wheat varieties, different in their grain productivity, determined that the latter (the mass of a grain from the head and the mass of 1000 grains) had positive correlation with the intensity of the flag leaf respiration during the blossoming phase of plants (r = 0.8–0.9). Our assumption stated that it was connected to the dependence of photorespiration intensity of leaves of different winter wheat varieties on the active surface area of plant roots. This assumption was used as a basis for the mentioned series of greenhouse experiments.

The data of the results of the comparative analysis of active surface areas of the root system for five winter wheat varieties testified that highly intensive varieties of winter wheat, Favorytka and Smuhlianka, had a larger active surface area of the root system and chlorophyll content in the leaves than Myronivska 808 plants (Table 4). It was demonstrated that the average value of the indices of active surface area of the root system and chlorophyll ($S_{r\ act}$ × chlorophyll) for intensive varieties was 5.41 ± 0.21. According to the data obtained, the index $S_{r\ act}$ × chlorophyll may be used to estimate the active surface area of the root system of varieties with chlorophyll content in the flag leaves with the error of up to 3.8 % for five winter wheat varieties.

Table 4. The content of chlorophyll in the flag leaves and the active surface area of the roots of different winter wheat varieties (the heading-blossoming phase)

Variety	Chlorophyll *a* + *b*	$S_{r\ act}$	$S_{r\ act}$ × × chlorophyll
Myronivska 808	3.60 ± 0.17	0.505 ± 0.08	1.82 ± 0.05
Smuhlianka	4.55 ± 0.16	1.114 ± 0.16	5.06 ± 0.15
Favorytka	4.52 ± 0.20	1.160 ± 0.12	5.24 ± 0.15
Poliska 90	6.10 ± 0.14	0.971 ± 0.08	5.92 ± 0.20
Donsky m/h	6.13 ± 0.16	0.882 ± 0.07	5.41 ± 0.16

Note. $S_{r\ act}$ – active surface area of the root system of winter wheat

The Figure presents the dependence of photorespiration intensity of the flag leaf in the heading-blossoming phase of winter wheat varieties Myronivska 808 and Smuhlianka on the active surface area of plant roots. The correlation coefficient for these indices was r = 0.805.

The data obtained also demonstrated the presence of considerable correlation between the chlorophyll content in the leaves and photorespiration intensity (r = 0.878).

CONCLUSIONS

It was determined that under drought the photosynthetic apparatus of a highly productive winter wheat variety Smuhlianka demonstrated higher stability than the photosynthetic apparatus of the moderately resistant variety Myronivska 808.

It was found that highly intensive varieties of winter wheat, Favorytka and Smuhlianka, had a larger active surface area of the root system and higher chlorophyll content in leaves, compared to Myronivska 808 plants, notable for lower grain productivity.

It was determined that there was considerable reliable correlation between the intensity of flag leaf photorespiration and the active surface area of the root system in winter wheat plants of varieties Myronivska 808 and Smuhlianka (r = 0.805).

It was found that there was considerable correlation (r = 0.878) between the intensity of flag leaf photores-

piration in the heading-blossoming phase and the sum of chlorophylls in these leaves.

It was established that the index $S_{r\ act}$ × chlorophyll may be used to estimate the active surface area of the root system of varieties with chlorophyll content in the flag leaves with the error of up to 3.8 % for five winter wheat varieties.

Вплив абіотичних факторів на фотосинтез і продукційний процес різних сортів озимої пшениці

Б. І. Гуляєв [1], Г. Б. Гуляєва [2], В. Ф. Патика [2]

e-mail: patykavolodymyr@gmail.com, ab_k@ukr.net

[1] Інститут фізіології рослин і генетики НАН України
Вул. Васильківська, 31/17, Київ, Україна, 03022
[2] Інститут мікробіології і вірусології імені Д. К. Заболотного НАН України
Вул. Академіка Заболотного, 154, Київ, Україна, 03680

Мета. Вивчення фотосинтезу і продукційного процесу у різних за зерновою продуктивністю сортів озимої пшениці, її зв'язку з площею активної поверхні кореневої системи за оптимальних умов, умов посухи і за дефіциту мінерального живлення. **Методи.** Фізіолого-біохімічні, газометричні, статистичні. **Результати.** Показано вплив різних умов мінерального живлення і ґрунтової посухи на інтенсивність фотосинтезу, фото- і темнового дихання, вміст пігментів у прапорцевому листку рослин озимої пшениці, а також взаємозв'язок цих показників з активною площею поверхні коренів рослин і зерновою продуктивністю різних за потенційною зерновою продуктивністю сортів озимої пшениці. **Висновки.** Встановлено, що фотосинтетичний апарат листків озимої пшениці високопродуктивного сорту Смуглянка за умов посухи виявився стійкішим порівняно з фотосинтетичним апаратом середньостійкого сорту Миронівська 808. У той же час високоінтенсивні сорти озимої пшениці Фаворитка і Смуглянка мали більшу площу активної поверхні кореневої системи і вміст хлорофілу в листках, аніж рослини сорту Миронівська 808, які при цьому відрізнялись меншою зерновою продуктивністю. Виявлено існування значного достовірного кореляційного зв'язку між інтенсивністю фотодихання прапорцевого листка і площею активної поверхні коренів у рослин озимої пшениці сортів Миронівська 808 і Смуглянка (*r* = 0,805). Знайдено також достовірну кореляційну залежність інтенсивності фотодихання прапорцевого листка у фазі колосіння-цвітіння і вмістом у цих листах суми хлорофілів (*r* = 0,878). Встановлено, що за показником $S_{к\ акт}$ × хлорофіл можна оцінювати площі активної поверхні коренів з похибкою до 3,8 % для п'яти сортів озимої пшениці.

Ключові слова: *Triticum aestivum* L., фотосинтез, фотодихання, площа активної поверхні кореневої системи, хлорофіл, продуктивність.

Влияние абиотических факторов на фотосинтез и продукционный процесс различных сортов озимой пшеницы

Б. И. Гуляев [1], А. Б. Гуляева [2], В. Ф. Патыка [2]

e-mail: patykavolodymyr@gmail.com, ab_k@ukr.net

[1] Институт физиологии растений и генетики НАН Украины
Ул. Васильковская, 31/17, Киев, Украина, 03022
[2] Институт микробиологии и вирусологии имени Д. К. Заболотного НАН Украины
Ул. Академика Заболотного, 154, Киев, Украина, 03680

Цель. Изучение фотосинтеза и продукционного процесса у различных по зерновой продуктивности сор-тов озимой пшеницы, ее связи с площадью активной поверхности корневой системы в оптимальных условиях, условиях засухи и дефицита минерального питания. **Методы.** Физиолого-биохимические, газометрические, статистические. **Результаты.** Показано влияние разных условий минерального питания и почвенной засухи на интенсивность фотосинтеза, фото- и темнового дыхания, содержание пигментов в флаговом листе растений озимой пшеницы, а также взаимосвязь этих показателей с активной площадью поверхности корней растений и зерновой продуктивностью различных по потенциальной зерновой продуктивности сортов озимой пшеницы. **Выводы.** Установлено, что фотосинтетический аппарат листьев озимой пшеницы высокопродуктивного сорта Смуглянка в условиях засухи оказался более устойчивым по сравнению с фотосинтетическим аппаратом среднеустойчивого к условиям засухи сорта Мироновская 808. В то же время высокоинтенсивные сорта озимой пшеницы Фаворитка и Смуглянка имели большую площадь активной поверхности корневой системы и содержание хлорофилла в листьях, чем растения сорта Мироновская 808, отличающиеся при этом меньшей зерновой продуктивностью. Выявлено существование значимой достоверной корреляционной связи между интенсивностью фотодыхания флагового листа и площадью активной поверхности корней у растений озимой пшеницы сортов Мироновская 808 и Смуглянка (*r* = 0,805). Обнаружена существенная корреляционная зависимость (*r* = 0,878) интенсивности фотодыхания флагового листа в фазе колошения-цветения от содержания в этих листьях суммы хлорофиллов. Установлено, что по показателю $S_{к\ акт}$ × хлорофилл можно оценить площадь активной поверхности корней с погрешностью до 3,8 % для пяти сортов озимой пшеницы.

Ключевые слова: *Triticum aestivum* L., фотосинтез, фотодыхание, площадь активной поверхности корневой системы, хлорофилл, продуктивность.

REFERENCES

1. *Kang Y, Khan S, Ma X.* Climate change impacts on crop yield, crop water productivity and food security – A review. *Progress in Natural Science.* 2009;**19**(12):1665–74.

2. *Hou R, Ouyang Z, Li Y, Wilson GV, Li H*. Is the change of winter wheat yield under warming caused by shortened reproductive period? *Ecol Evol*. 2012;**2**(12): 2999–3008.
3. *Zhao J, Hartmann H, Trumbore S, Ziegler W, Zhang Y*. High temperature causes negative whole-plant carbon balance under mild drought. *New Phytologist*. 2013;**200**(2):330–9.
4. *Chaves MM, Pereira JS, Maroco J., Rodrigues ML, Ricardo CPP, Osorio ML, Carvalho I, Faria T, Pinheiro C*. How plants cope with water stress in the field? Photosynthesis and Growth. *Ann Bot*. 2002;**89**(7): 907–16.
5. *Torriani DS, Calanca P, Schmid S, Beniston M, Fuhrer J*. Potential effects of changes in mean climate and climate variability on the yield of winter and spring crops in Switzerland. *Clim Res*. 2007;**34**(1):59–69.
6. *Gulyaev BI.* Photosynthesis and plant productivity: problems, achievements and prospects of researches. *Physiology and Biochemistry of Cultivated Plants*. 1996;**28**(1–2):15–35.
7. *Sharkey TD*. Effects of moderate heat stress on photosynthesis: importance of thylakoid reactions, rubisco deactivation, reactive oxygen species, and thermotolerance provided by isoprene. *Plant, Cell and Environment*. 2005;**28**:269-77.
8. *Gollan T, Turner NC, Schulze ED*. The responses of stomata and leaf gas exchange to vapour pressure deficits and soil water content III. In the sclerophyllous woody species *Nerium oleander. Oecologia*. 1985;**65**(3):35662.
9. *Stasyk OO*. Photorespiration and its physiological significance. *Plant physiology: Problems and prospects*. In 2 vol. Vol. 1. Kyiv, Logos. 2009;170–99.
10. *Waines JG, Ehdaie B*. Dom**e**stication and crop physiology: roots of green- revolution wheat. *Ann Bot*. 2007;**100**(5):991–8.
11. *Gulyaev BI, Karlova GB*. Root surface area of plants of different grain productivity of winter wheat cultivars. *Journal of Kharkiv National Agrarian University*. Series Biology. 2011;**3**(24):56–60.
12. *Fageria NK, Moreira A*. The role of mineral nutrition on root growth of crop plants. *Advances in Agronomy*. Burlington, Acad. Press. 2011;Vol. 110:251–331.
13. *Comas LH, Becker SR, Cruz VM, Byrne PF, Dierig DA*. Root traits contributing to plant productivity under drought. *Front Plant Sci*. 2013;4:442.
14. *Lynch J*. Root architecture and plant productivity. *Plant Physiol*. 1995;**109**(1): 7–13.
15. 15. *Walker TS, Bais HP, Grotewold E, Vivanco JM*. Root exudation and rhizosphere biology. *Plant Physiol*. 2003;**132**(1):4451.
16. *Gulyaev BI, Iliyashuk EM, Mitrofanov BA, Rozhko II, Golik KN, Gojsa NI, Antonenko VS.* Photosynthesis and production process. Kyiv, Naukova Dumka. 1983; 143 p.
17. *Photosynthesis* and bioproductivity: determination methods. Eds A. T. Mokronosov, A. H. Kovaliov. Moscow, Agropromizdat. 1989; 459 p.
18. 18. *Hiscox JD, Israelstam GF*. A method for the extraction of chlorophyll from leaf tissue without maceration. *Can J Bot*. 1979;**57**(12):1332–4.