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LEAF WATER-USE EFFICIENCY PARAMETERS OF *Fagopyrum esculentum* Moench PLANTS AS INFLUENCED BY ENDOGENOUS AND EXOGENOUS FACTORS

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Abstract

Sustainable development of contemporary agriculture is hampered by a number of facotors, one of which is the increasing aridization of the planet's climate. In this regard, the water use efficiency (WUE) of plants is of great importance. In this paper the data of long-term field experiments are submitted which illustrate the influence of photosynthesis rate, transpiration rate, stomatal conductance and, also, growing conditions on the buckwheat plant WUE. The purpose of the study is to identify the specific peculiarities of WUE of common buckwheat (*Fagopyrum esculentum* Moench) plants with regard to photosynthesis and production processes. A total of 22 varieties of common buckwheat (K-406 and K-1709 — local populations; Kalininskaya, Bogatyr, Shatilovskaya 5 — old varieties; Dikul, Dozhdik, Demetra, Devyatka, Design — modern commercial varieties; Bashkirskaya krasnostebelnaya, Batyr, Usha, Chatyr-Tau, Inzerskaya, Design 2, P 66, P 69, P 70, P 84, P 85, SPR 52 — varieties which are perspective for different conditions) were examined. Plants were grown on the experimental field of buckwheat breeding lab of FSC of Legumes and Groats Crops (Orel District, Orel Province) in 2010-2015. A plot area was 10 m^2. The plots' locations were random, with fourfold replication. Photosynthesis rate (PI), transpiration intensity (TI), and stomatal conductance were measured according to the original method of Heinz Walz GmbH (Germany) using a GFS-3000 FL portable gas analyzer. The assessment was conducted on 5-7 plants typical for the genotype, growing in the middle of the plot, which leaves were not damaged by pests and diseases. The measurements were carried out in real time at the main growth phases (branching, flowering + 10 days, flowering + 20 days, flowering + 30 days) from 7 AM to 7 PM with a frequency of 3 hours. In the measuring chamber of the device the light intensity was maintained at 1000 μmol photons$\cdot m^{-2} \cdot s^{-1}$, the air temperature was 25 °C. The measurements were performed on the 3rd leaves from the top. WUE was calculated as the ratio of the values of the photosynthesis and transpiration intensities. The grain yield from each plot was evaluated both by direct weighing and by structural analysis of plants. As a result of the research, it was found that the buckwheat WUE values significantly depend on both growing conditions and hereditary characteristics. Depending on the weather conditions of the growing season, the WUE varied from 1.03 to 2.08 μmol CO_2/mmol H_2O. Its highest value (2.08 μmol CO_2/mmol H_2O) was noted in 2012 when the weather was relatively favorable for plant growth and development. In ontogeny, the maximum efficiency of water use for the photosynthesis was recorded at branching (2.43 μmol CO_2/mmol H_2O on average) and mass filling of seeds (1.78 μmol CO_2/mmol H2O/m2s), and the lowest WUE values were during budding and flowering (1.17 μmol CO_2/mmol H_2O on average). In the daytime, the most CO_2 molecules per unit of evaporated water were assimilated from 9 AM to 11 AM when the highest intensity of leaf photosynthesis and moderate transpiration activity were observed. The correlation coefficient between WUE and the intensity of leaf photosynthesis was positive (r = 0.69, $p < 0.05$), and it was negative between WUE and the intensity of transpiration (r = –0.89, $p < 0.05$). Buckwheat varieties significantly differ in terms of WUE values. As a result of breeding, the value of WUE increased (P = 0,95) by 20.5 % on average, which was due to an increase in PI by 29.0 %, TI by 7.9 %, and stomatal conductance by 18.1 % on average.

Keywords: *Fagopyrum esculentum*, buckwheat, rate of photosynthesis, rate of transpiration, water-use efficiency, crop yield

Modern agriculture is low sustainable, including due to increasing climate aridization [1, 2]. In this regard, the evaporation of water by plants [3-5], which depend on both exogenous and endogenous factors of growth and development [6-8], are important. The moisture regime and air temperature as exogenous factors [9] and photosynthesis and leaf transpiration as endogenous factors, due to their physiological position in the production process and the plant's defense system [10, 11], play the determining role. Many researchers point to the importance of studying the efficiency of water use by plant leaves [12, 13].

Water use efficiency (WUE) is usually assessed using three indicators. This is the assimilation-transpiration ratio (ATR), i.e., the ratio of the current values of the intensity of photosynthesis to transpiration; transpiration productivity (TP), i.e., the dry biomass formed per unit of water transpired by the plant; isotope discrimination of carbon ($\Delta^{13}C$) that characterizes ATR in a leaf [10]. Despite certain differences, the basis of all these indicators is the conjugacy of gas and water exchange processes at different levels of plant organization.

When studying the relationships between the parameters that determine WUE and drought resistance, QTL (quantitative trait loci) associated with water use efficiency were established in 120 F_2 wheat hybrids, and it was shown that biomass accumulation is positively correlated with ATR, leaf specific surface density (SSD) and trancpiration intencity (TI), but negatively with $\Delta^{13}C$ [9].

The study of these issues is also relevant for such a popular crop on the world food market as buckwheat which acreage expansion is largely hampered by the low plant adaptability [14]. It is known that buckwheat consumes 2-3 times more water than millet and other crops [15-17]. Moreover, during selection, plant resistance to moisture limitation not only does not increase, but has a pronounced tendency to decrease [18]. In modern buckwheat varieties, grain yield sharply decreases in dry and hot weather [19].

In this work, we for the first time obtained data on the efficiency of water use by the leaves of buckwheat plants depending on the growth phase, time of day and weather conditions of the growing season, and also described the nature of its relationship with the intensity of photosynthesis, transpiration and seed productivity.

The purpose of the study is to identify species-specific characteristics of water consumption during photosynthesis and the production process in common buckwheat (*Fagopyrum esculentum* Moench) plants.

Materials and methods. The objects of study were 22 varieties of common buckwheat. Of these, 10 were created in the course of selection from local populations to the best modern zoned varieties. These are K-406 and K-1709 (local populations); Kalininskaya, Bogatyr, Shatilovskaya 5 (old varieties); Dikul, Dozhdik, Demeter, Devyatka, Design (modern zoned varieties). Other 12 varieties were studied as promising for different conditions: Bashkir Krasnostebelnaya, Batyr, Usha, Chatyr-Tau, Inzerskaya, Design 2, R 66, R 69, R 70, R 84, R 85, SPR 52.

The studied varieties were grown in the selection crop rotation of the Federal Research Center for Leguminous and Cereal Crops (Oryol Province, Oryol District) in 2010-2015 on 10 m^2 plots in 4 repetitions using a randomized design. Crop care and harvesting were carried out according to methodological recommendations for the region.

Additionally, for five buckwheat varieties (K-406, K-1709, Bogatyr, Dikul, Dozhdik), two series of model pot experiments were conducted to study the daily dynamics of photosynthesis intensity, transpiration intensity and water use efficiency. For this purpose, plants were grown in special 9-liter pots (5 plants typical for the variety in each pot, 4-fold repetition) at soil moisture of 30 and 70% of the full moisture capacity.

In the pot tests, the analyzed indicators were determined for each variety sample. In small-plot experiments, 5-7 plants typical for the genotype and not damaged by pests or diseases were examined. Measurements were carried out in real time during the main growth phases (branching, flowering + 10 days, flowering + 20 days, flowering + 30 days) on the physiologically mature 3rd leaf from the top of of the main stem.

The photosynthesis intensity (PI), the transpiration intensity (IT) and stomatal conductance (SC) were assessed by the original method of Heinz Walz GmbH (Germany) using a portable gas analyzer GFS-3000 FL. Measurements were carried out from 7AM to 7PM, with 3-hour interval, in the pot test, and from 8AM to 11AM in the small-plot experiment. In the measuring chamber of the device, the light intensity was maintained at 1000 μmol photons $\cdot m^{-2} \cdot s^{-1}$, the air temperature at 25 °C.

WUE was determined by calculating the ratio of the current values of photosynthesis intensity to the values of transpiration intensity [10, 20].

Grain yield was assessed for each plot of the variety by weighing (VK-600 scales, ZAO Massa-K, Russia) and by structural analysis of 15 plants in 4 repetitions.

Statistical processing (variance and correlation analysis) was carried out using the Microsoft Excel 2013 and Statistica v. 10.0 software packages (StatSoft, Inc., USA). The significance of differences was determined by Student's *t*-test at P = 0.95. Mean values (*M*) and standard deviations (±SD) were calculated.

Results. The years of investigations differed in weather conditions. The year 2010 was the most extreme, throughout of growing season, there was 54.9% less precipitation, and the average monthly air temperature was 5.5 °C higher than the long-term average. The conditions in 2012 turned out to be the most comfortable for buckwheat plants: the amount of precipitation and the average monthly temperature during the growing season were close to the long-term averages. The weather conditions in 2011 and 2013-2015 during certain growth phases were harsh, but not extreme.

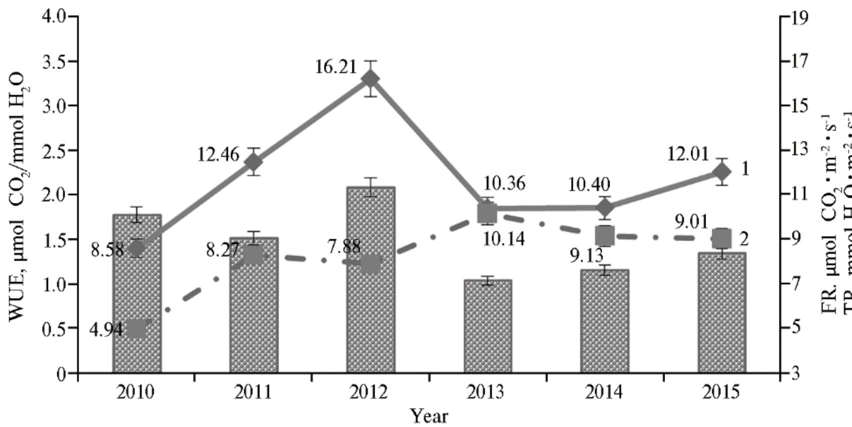

Fig. 1. Water use efficiency (WUE) (diagram)**, photosynthesis rate** (FR) (1) **and transpiration rate** (TR) (2) **in the leaves of common buckwheat (*Fagopyrum esculentum* Moench) in different years during the flowering phase + 10 days** (average of 22 variety samples, for each variety sample *n* = 5, *M*±SD; Federal Research Center of Leguminous and Cereal Crops, Oryol Province, Oryol District). For descriptions of variety samples, see the Materials and methods section.

It has been found out that in buckwheat plants, as in other agricultural crops [11, 21, 22], the efficiency of water use is closely related to weather conditions. Its value during the years of research varied from 1.03 to 2.08 μmol CO_2/mmol H_2O. The highest efficiency of water use for photosynthesis was observed in 2012, the lowest in 2013-2015. In 2012, the WUE value was higher (at P = 0.95) by an average of 14.9% compared to 2010, by 27.4% vs. 2011, by 50.5% vs. 2013, by 44.7% vs. 2014, and by 35.6% vs. 2015. The influence of weather conditions during the growing season on the efficiency of water use was mediated through the impact on the processes of transpiration and photosynthesis (Fig. 1).

The correlation coefficient between WUE and the leaf photosynthesis intensity was positive ($r = +0.69$, $p < 0.05$), and between WUE and the transpiration intensity negative ($r = -0.89$, $p < 0.05$). Therefore, in 2012, high water use efficiency was due to increased photosynthesis intensity and moderate transpiration activity. There were favorable weather conditions for the growing of buckwheat plants, so there was no particular need to spend a large amount of energy on water evaporation, organic matter was mainly formed and the yield was the highest, the 3.5 t/ha [18, 19].

In the more severe weather conditions of 2013-2015, plants needed protection from overheating, which was ensured by increased transpiration to the detriment of photosynthesis: the efficiency of water use to maintain photosynthesis in these years was reduced compared to more favorable conditions on average by 34.6%, and seed productivity by 25.4% (P = 0.95).

However, in stressful situations, the plant physiological responses was somewhat different. In 2010, under pronounced soil and air drought (hydrothermal coefficient HTC = 0.36), in order to avoid cell dehydration and maintain their viability, plants were forced to use water and energy very sparingly. This was achieved due to the low rate of transpiration and photosynthesis, which resulted in a decrease in the efficiency of the production process as a whole. In model pot tests, when soil moisture decreased from 70 to 30% of the total moisture capacity, the photosynthesis intensity of buckwheat plants decreased 4.4-fold, the transpiration intensity by more than 35%, and productivity by 43.6% (P = 0.95).

As a result, in 2010, the efficiency of water use in plants of all varieties was above average, and the total and seed productivity was less on average by 66.6% (P = 0.95) compared to less extreme growing conditions (Table 1).

1. **Water use efficiency** (WUE, μmol CO_2/mmol H_2O)**, seed weight and dry weight of above-ground organs in 11 varieties of common buckwheat (*Fagopyrum esculentum* Moench) in different years** (M±SD; Federal Research Center for Leguminous and Cereal Crops, Oryol Province, Oryol District)

Paramter	Year					
	2010	2011	2012	2013	2014	2015
WUE	1.77±0.24	1.51±0.12	2.08±0.26	1.03±0.08	1.15±0.10	1.34±0.14
Dry mass of aboveground organs, g/plant	3.20±0.40	5.10±0.65	6.70±0.13	6.04±0.55	5.09±0.46	5.38±0.49
Seed weight, g/plant	0.52±0.17	1.41±0.45	1.77±0.29	1.60±0.48	1.54±0.37	1.51±0.35

N o t e. The WUE values are given for the period of fruits formation (flowering phase + 10 days); for their calculation, we used data obtained from 8.00 a.m. to 11.00 a.m. (for each variety $n = 5$). The dry weight of above-ground organs was determined at the stage of harvest ripeness (for each variety, 15 plants were analyzed in 4 replicates). For descriptions of variety samples, see the Materials and methods section.

A sharp decrease in the intensity of photosynthesis during drought and, as a consequence, productivity can be caused by both an insufficient supply of water and nutrients to the leaves due to low transpiration activity, and a disruption in the functioning of the reaction centers of photosystems [23].

The efficiency of water use by buckwheat plants varied during ontogenesis from 1.17 to 2.43 μmol CO_2/mmol H_2O. The value was highest at branching stage and during mass filling of seeds. WUE during vegetative growth period was on average 52 and 34% higher compared to the stages flowering + 10 days and flowering + 30 days. The variability of the indicator was closely related to the photosynthetic and transpiration activities of the leaves.

An increase in the intensity of photosynthesis was observed mainly before the flowering phase + 20 days, and then sharply decreased, while the transpiration rate was the highest during the flowering phase + 10 days, and during the period of vegetative growth and mass filling of seeds (flowering phase + 20 days) it was minimal (4.31 mmol $H_2O \cdot m^{-2} \cdot s^{-1}$) or moderate (5.92 mmol $H_2O \cdot m^{-2} \cdot s^{-1}$), which correspondingly affected the efficiency of water use by plants (Fig. 2).

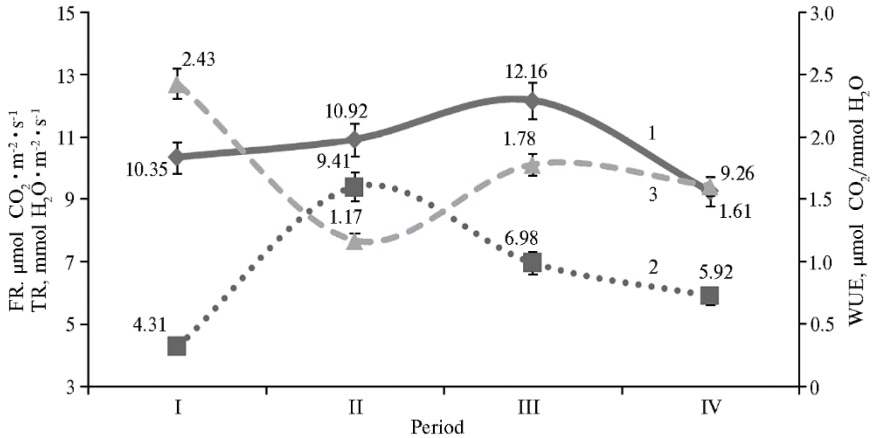

Fig. 2. Photosynthesis rate (FR) (1)**, transpiration rate** (TR) (2) **and water use efficiency** (WUE) (3) **in the leaves of common buckwheat (*Fagopyrum esculentum* Moench) accessions K-406, K-1709, Kalininskaya, Bogatyr, Shatilovskaya 5, Demeter, Dozhdik, Dikul, Inzerskaya, Devyatka, Design in different phases of growth and development:** I — vegetative growth, II — flowering + 10 days, III — flowering + 20 days, IV — flowering + 30 days (average of 11 variety samples, for each variety sample for each variety sample $n = 5$, $M \pm SD$; Federal Research Center of Leguminous and Cereal Crops, Oryol Province, Oryol District, 2013-2015). For descriptions of variety samples, see the Materials and methods section.

The manifestation of a certain disconnect between the intensity of photosynthesis and transpiration is explained by the fact that CO_2 and H_2O molecules use one route into the leaf, through the stomata. However, the diffuse gradient driving transpiration is approximately 50 times greater than that driving carbon dioxide uptake, which is reflected in the efficiency of water use by plants during ontogeny [10, 24). In crops, it is typically low because plants lose nearly 100 times more water than they assimilate equivalent units of carbon through photosynthesis. To increase crop production, it is important to pay attention to increasing WUE in cultivated plant species [11]. An analysis of the water use efficiency of soybean plants showed that a 1% increase in WUE in leaf blades at the field scale leads to an increase in WUE by approximately 10% [25]. It is proposed to use this indicator as a secondary criterion for selecting crop genotypes based on seed yield [26]. It has been established that, in absolute value, the closest to the WUE indicator in field conditions is the so-called instantaneous (i) measured WUE (WUEi) of the leaf calculated from the respiration value [27].

During daylight hours, the highest rate of CO^2 assimilation per unit amount of water evaporated by a unit of leaf surface in buckwheat plants was observed in the pre-lunch time (from 9AM to 11AM), with an increase in solar radiation, when the air temperature is still low (20-25 °C). During this period, there was a peak in photosynthetic activity and moderate transpiration. After 11AM, WUE values decreased noticeably, primarily due to a pronounced drop in photosynthetic activity and increased transpiration due to high air temperature and insolation (Fig. 3). Obviously, in the afternoon, the transpiration process in the leaves is aimed to a greater extent at preventing overheating of the above-ground organs, which reduces the possibilities of photosynthesis. A decrease in WUE at midday was also observed in plants of such a heat-loving crop as soybean, which is also explained by increased transpiration rates and an increase in PAR (photosynthetically active radiation) [27].

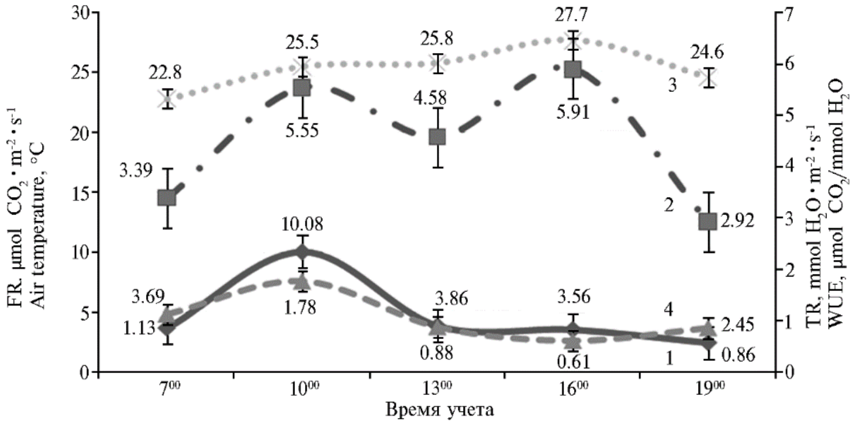

Fig. 3. Daily dynamics of photosynthesis rate (PR) (1)**, transpiration rate** (TR) (2)**, air temperature** (3) **and water use efficiency** (WUE) (4) in the leaves of common buckwheat (*Fagopyrum esculentum* Moench) varieties K-406, K-1709, Bogatyr, Dikul, Dozhdik during the flowering phase + 20 days according to two series of vegetation tests (n = 5, M±SD; Federal Research Center of Leguminous and Cereal Crops, Oryol Province, Oryol District, 2014-2015).

2. Photosynthesis rate, transpiration rate, stomatal conductivity and water use efficiency in 10 local populations and varieties of common buckwheat (*Fagopyrum esculentum* Moench) bred during different periods at lowering + 20 days (for each sample n = 5, M±SD; Federal Scientific Center for Grain Legumes and Cereal Crops, Oryol Province, Oryol District, 2013-2015)

Variety sample	Photosynthesis rate, μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$	Transpiration rate, mmol $H_2O \cdot m^{-2} \cdot s^{-1}$	Stomatal conductance, mol $H_2O \cdot m^{-2} \cdot s^{-1}$	Water use efficiency, μmol CO_2/mmol H_2O
Local populationsи (Oryol Province)				
K-406	9.55±0.30	6.20±0.21	0.452±0.025	1.54±0.28
K-1709	11.53±0.29	7.28±0.20	0.441±0.023	1.58±0.30
Varieties bred in 1930-1960				
Kalininskaya	11.76±0.31	7.61±0.22	0.447±0.024	1.55±0.24
Bogatyr	12.35±0.27	7.37±0.19	0.465±0.025	1.68±0.10
Shatilovskaya 5	9.76±0.25	6.47±0.17	0.472±0.027	1.51±0.31
Varieties bred in 1990-2010				
Demeter	13.97±0.29	8.07±0.17	0.551±0.027	1.73±0.27
Rain	13.28±0.27	7.36±0.19	0.564±0.026	1.80±0.28
Dikul	15.58±0.28	7.84±0.21	0.553±0.025	1.99±0.44
Devyatka	13.22±0.30	6.49±0.20	0.480±0.024	2.04±0.51
Design	11.96±0.31	6.58±0.22	0.492±0.026	1.82±0.36
LSD_{05}	0.31	0.22	0.027	0.52

It is important to note that as a result of selection, the efficiency of water use by buckwheat plants has increased significantly, primarily due to an increase in the intensity of photosynthesis during the formation and mass filling of seeds. During the period of selection of buckwheat crops from local populations to the best modern zoned varieties, the values of WUE of plants became higher (P = 0.95) on average by 20.5%, PI by 29.0%, TI by 7.9%, which was significantly due to increased stomatal conductance of leaves (Table 2). Similar changes are observed in the selection of durum and soft wheat, during the transition from old varieties to modern ones [28, 29].

This is to a certain extent consistent with evolutionary changes in plants, accompanied by an increase [30, 31] or optimization of water use [31, 32]. The strategy is to open the stomata enough to allow the required amount of CO_2 molecules to be absorbed during photosynthesis while avoiding tissue dehydration during transpiration. In this case, the ratio of PI to SC remains fairly constant over a wide range of factors [32].

We have identified largely similar trends in the nature of manifestation in other cultivated plant species [22, 33], despite certain differences. For example, in spring and winter wheat, under the same weather and agrotechnical growing conditions, the efficiency of water use by plants was on average 23.4 and 35.1% higher than that of buckwheat (Fig. 4).

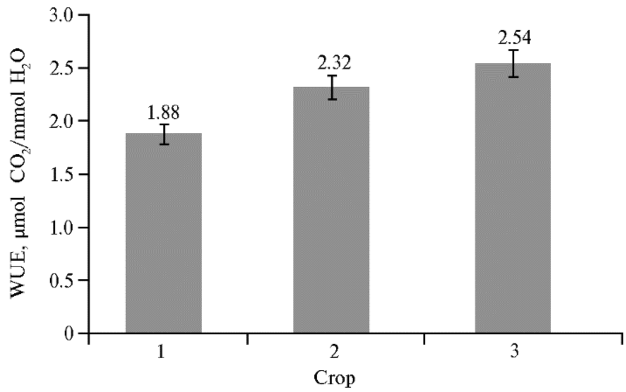

Fig. 4. Water use efficiency during grain formation in different agricultural crops: 1 — buckwheat *Fagopyrum esculentum* Moench of modern zoned varieties Demetra, Dozhdik, Dikul, Devyatka, Design (for each variety $n = 5$, $M\pm$SD, Federal Research Center for Leguminous and Cereal Crops, Oryol Province, Oryol district, 2013-2015); 2 — spring wheat *Triticum aestivum* L. varieties Burlak, Voronezhskaya 13, Voronezhskaya 18, Rima, Ulyanovskaya 105, Chernozemnouralskaya 2, Voronezhskaya 20, Liza, Tulaikovskaya Nadezhda, Khutoryanka, Yubileinaya 80, Arsea, Al Varis, Zlata, Radmira, *Triticum durum* Desf. varieties Donela M, Melodiya Dona, Bezenchukskaya Niva, Bezenchukskaya 210, Donskaya Elegiya); 3 — winter wheat *Triticum aestivum* L. varieties Moskovskaya 40, Moskovskaya 39, Nemchinovskaya 17, Asket, Povolzhskaya Niva, Angelina, Morozko, Moskovskaya 56, Biryuza, Oktava 15, Chernozemka 130, Nemchinovskaya 57, Yuka, Ariadna, Donera ($n = 5$, $M\pm$SD) [33] (Federal Research Center for Leguminous and Cereal Crops, Oryol Province, Oryol District, 2017-2019).

Over the years of research, WUE changed in spring wheat plants from 1.63 to 2.73, in winter wheat plamts from 1.88 to 4.19 μmol CO_2/mmol H_2O with a significant impact on the yield, mainly in harsh weather conditions of the growing season. In the dry year of 2018, according to this indicator, high-yielding varieties of spring wheat outperformed medium- and low-yielding varieties by an average of 70% (P = 0.95) [22]. In winter wheat, a close relationship between WUE and the content of protein and gluten in the grain was revealed [33].

In *Fagopyrum esculentum* plants, high efficiency of water use by plants and seed yield were observed mainly in favorable weather conditions during the growing season. This indicates their lower adaptive capabilities, especially under drought conditions, obviously due to the formation of a larger (by 40.8%) evaporative leaf surface, increased (by 21.2%) transpiration intensity and decreased (by 13.9%) photosynthetic activity compared to spring and winter wheat. The identified species characteristics of cultivated plants are apparently due to different conditions of their evolution. Buckwheat, as is known, is a subtropical crop, originated from Southern China, under conditions of increased humidity and high air temperatures [34], while wheat, according to N.I. Vavilov [35], originated from South-

West Asia, the places with an arid climate.

The correctness of this assumption is also evidenced by the results of research by D.A. Ronzhina et al. [36]. Studying the structural and functional parameters of leaves in 21 plant species growing in different water supply conditions, they came to the conclusion that with a decrease in the degree of hydrophilicity in the helophyte-hygrophyte series, a structural restructuring of the leaf occurs in the direction of increasing its density and dry matter content, which is accompanied by a decrease in speed transpiration and a natural increase in water use efficiency [36).

The efficiency of water use by plants can be increased using both agrotechnical and breeding methods. According to E.I. Koshkin [9], the simplest way for C3 grain crops is to combine the period of accumulation of maximum biomass with the coolest weather conditions, for which it is necessary to change the sowing time. In this case, selection should be aimed at activating the processes of initial growth, which will lead to an increase in the leaf surface index, PAR absorption and, as a consequence, an increase in WUE [9].

To achieve this goal in buckwheat, in our opinion, it is important to improve the light transmission capacity of the agrocenosis by regulating the seeding rate and optimizing plant architecture. It is advisable to select forms with a smaller leaf surface but dense leaf blades, that is, to select for xeromorphism. New varieties should also have increased photosynthetic activity with moderate transpiration. Work in this direction may well be successful, since the buckwheat gene pool is characterized by wide polymorphism in parameters of photosynthetic and transpiration activity [37, 38].

To summarize, we note that, unlike spring and winter wheat, in buckwheat *Fagopyrum esculentum* Moench, high efficiency of water use and seed yield were observed mainly under favorable weather conditions during the growing season. This indicates lower adaptive capabilities (especially when exposed to drought) due to the formation of a larger (by 40.8%) evaporative leaf surface, increased (by 21.2%) transpiration intensity and decreased (by 13.9%) photosynthetic activity . The identified differences between cultivated plant species are largely due to the different conditions of their evolutionary formation. Buckwheat, as is known, is a subtropical crop, the development of which took place in Southern China, with increased moisture and high temperatures.

Thus, the water use efficiency (WUE) of common buckwheat plants is significantly influenced by hereditary characteristics and weather conditions of growth. At elevated air temperatures and limited precipitation, WUE decreases, and under favorable weather conditions it increases. Of the endogenous factors, the intensity of leaf photosynthesis has a positive effect on plant WUE ($r = +0.69$, $p < 0.05$), while the intensity of transpiration has a negative effect ($r = -0.89$, $p < 0.05$). As a result of selection, the value of WUE increased ($P = 0.95$) by an average of 20.5%, which was due to an increase in the intensity of photosynthesis by 29.0%, the intensity of transpiration by 7.9%, including due to an increase in stomatal conductance of leaves on average by 18.1%. This had a positive effect on the growth of crop yields only under optimal growing conditions, because the plants' resistance to air and soil drought decreased. Selection of forms with increased photosynthetic activity and moderate transpiration can be considered as one of the priority areas of crop selection.

REFERENCES

1. Kulikov A.I., Ubugunov L.L., Mangataev A.Ts. *Aridnye ekosistemy*, 2014, 3(60): 5-13 (in Russ.).
2. Stuart D., Schewe R.L. Constrained choice and climate change mitigation in US agriculture: structural barriers to a climate change ethic. *Journal of Agricultural and Environmental Ethics*,

2016, 29: 369-385 (doi: 10.1007/s10806-016-9605-z).
3. Zhang Y., Yu X., Chen L., Jia G. Whole-plant instantaneous and short-term water-use efficiency in response to soil water content and CO_2 concentration. *Plant Soil*, 2019, 444: 281-298 (doi: 10.1007/s11104-019-04277-6).
4. Tränkner M., Jákli B., Tavakol E., Geilfus C.-M., Cakmak I., Dittert K., Senbayram M. Magnesium deficiency decreases biomass water-use efficiency and increases leaf water-use efficiency and oxidative stress in barley plants. *Plant Soil*, 2016, 406: 409-423 (doi: 10.1007/s11104-016-2886-1).
5. Karthika G., Kholova J., Alimagham S., Ganesan M., Chadalavada K., Kumari R., Vadez V. Measurement of transpiration restriction under high vapor pressure deficit for sorghum mapping population parents. *Plant Physiology Reports*, 2019, 24: 74-85 (doi: 10.1007/s40502-019-0432-x).
6. Li Y., Li H., Li Y., Zhang S. Improving water-use efficiency by decreasing stomatal conductance and transpiration rate to maintain higher ear photosynthetic rate in drought resistant wheat. *The Crop Journal*, 2017, 5(3): 231-239 (doi: 10.1016/j.cj.2017.01.001).
7. Zhu X., Yu G., Wang Q., Hu Z., Han S., Yan J., Wang Y., Zhao L. Seasonal dynamics of water use efficiency of typical forest and grassland ecosystems in China. *Journal of Forest Research*, 2014, 19(1): 70-76 (doi: 10.1007/s10310-013-0390-5).
8. Damour G., Simonneau T., Cochard H., Urban L. An overview of models of stomatal conductance at leaf level. *Plant, Cell & Environment*, 2010, 33(9): 1419-1438 (doi: 10.1111/j.1365-3040.2010.02181.x).
9. Koshkin E.I. Fiziologicheskie *osnovy selektsii rasteniy* [Physiological basis of plant breeding]. Moscow, 2014 (in Russ.).
10. Koshkin E.I. *Fiziologiya ustoychivosti sel'skokhozyaystvennykh kul'tur* [Physiology of crop resistance]. Moscow, 2010 (in Russ.).
11. Bramley H., Turner N.C., Siddique K.H.M. Water use efficiency. In: *Genomics and breeding for climate-resilient crops* /C. Kole (ed.). Springer, Berlin, Heidelberg, 2013: 225-268 (doi: 10.1007/978-3-642-37048-9_6).
12. Zhou L., Meng X., Zhang Z., Wu Q. Association analysis of growth characteristics, WUE, and RUE of rice in cold region under different irrigation patterns. *Journal of The Institution of Engineers (India): Series A*, 2020, 101: 421-431 (doi: 10.1007/s40030-020-00452-6).
13. Moradgholi A., Mobasser H., Ganjali H., Fanaie H., Mehraban A. WUE, protein and grain yield of wheat under the interaction of biological and chemical fertilizers and different moisture regimes. *Cereal Research Communications*, 2022, 50: 147-155 (doi: 10.1007/s42976-021-00145-1).
14. Fesenko A.N., Fesenko I.N. *Zemledelie*, 2017, 3: 24-26 (in Russ.).
15. Vazhov V.M. *Grechikha na polyakh Altaya* [Buckwheat in the fields of Altai]. Moscow, 2013 (in Russ.).
16. Vavilov P.P., Gritsenko V.V., Kuznetsov V.S. *Rastenievodstvo* [Crop production]. Moscow, 1986 (in Russ.).
17. Lakhanov A.P., Kolomeychenko V.V., Fesenko N.V., Napolova G.V., Muzalevskaya R.S., Savkin V.I., Fesenko A.N. *Morfofiziologiya i produktsionnyy protsess grechikhi* [Morphophysiology and production process of buckwheat]. Orel, 2004 (in Russ.).
18. Amelin A.V., Fesenko A.N., Chekalin E.I., Zaikin V.V. Adaptiveness of productivity and photosynthesis in buckwheat (*Fagopyrum esculentum* Moench) landraces and varieties produced at different periods. *Sel'skokhozyaistvennaya biologiya* [*Agricultural Biology*], 2016, 51(1): 79-88 (doi: 10.15389/agrobiology.2016.1.79eng).
19. Amelin A.V., Fesenko A.N., Zaikin V.V., Boyko T.V. *Agrarnyy nauchnyy zhurnal*, 2014, 11(23): 3-6 (in Russ.).
20. Polley W.H. Implications of atmospheric and climate change for crop yield and water use efficiency. *Crop Sciense*, 2002, 42(1): 131-140 (doi: 10.2135/cropsci2002.1310).
21. Ruggiero A., Punzo P., Landi S., Costa A., Van Oosten M.J., Grillo S. Improving plant water use efficiency through molecular genetics. *Horticulturae*, 2017, 3(2): 31 (doi: 10.3390/horticulturae3020031).
22. Amelin A.V., Chekalin E.I., Zaikin V.V., Ikusov R.A., Shishkin A.S. *Vestnik Kurskoy GSKhA*, 2022, 6: 6-12 (in Russ.).
23. Udovenko G.V. V sbornike: *Fiziologicheskie osnovy selektsii rasteniy* [In: Physiological basis of plant breeding]. St. Petersburg, 1995, 2: 293-352 (in Russ.).
24. Alekhina N.D, Balnokin Yu.V., Gavrilenko V.F., Zhigalova T.V. *Fiziologiya rasteniy* [Plant physiology]. Moscow, 2007 (in Russ.).
25. Gorthi A. *Quantifying water use efficiency at leaf and field-scales for soybean, miscanthus and switchgrass. Doctoral Thesis.* Purdue University, 2017.
26. Amoanimaa-Dede H., Su C., Yeboah A., Zhou H., Zheng D., Zhu H. Growth regulators promote soybean productivity: a review. *PeerJ*, 2022, 10: e12556 (doi: 10.7717/peerj.12556).
27. Kharchuk O.A., Kirillov A.F., Budak A.B. *Evraziyskiy Soyuz Uchenykh*, 2018, 11-1(56): 42-46 (in Russ.).

28. Li L.H., Chen S.B. Study on root function efficiency of spring wheat under different moisture condition. *Sci. Agric. Sin.*, 2002, 35: 867-871 (in Chinese).
29. Fan X.-W., Li F.-M., Xiong Y.-C., An L.-Z., Long R.-.J. The cooperative relation between non-hydraulic root signals and osmotic adjustment under water stress improves grain formation for springwheat varieties. *Physiologia Plantarum*, 2008, 132(3): 283-292 (doi: 10.1111/j.1399-3054.2007.01007.x).
30. Li Y.Y., Zhang S.Q., Shao M.A. Interrelationship between water use efficiency and nitrogen use efficiency of different wheat evolution materials. *Chinese Journal of Applied Ecology*, 2003, 14(9): 1478-1480 (in Chinese).
31. Song L., Li F.M., Fan X.W., Xiong Y.C., Wang W.Q., Wu X.B., Turner N.C. Soil water availability and plant competition affect the yield of spring wheat. *European Journal of Agronomy*, 2009, 31(1): 51-60 (doi: 10.1016/j.eja.2009.03.003).
32. Bacon M. *Water use efficiency in plant biology*. Armsterdam, 2004.
33. Amelin A.V., Chekalin E.I., Zaikin V.V., Mazalov V.I., Ikusov R.A. Biochemical grain quality indicators and photosynthetic rate of leaves in modern varieties of winter wheat. *IOP Conference Series: Earth and Environmental Science*, 2021, 848: 012096 (doi: 10.1088/1755-1315/848/1/012096).
34. Ohnishi O. Distribution and classification of wild buckwheat species. 1. Cymosum group. *Fagopyrum,* 2010, 27: 1-8.
35. Vavilov N.I. *Trudy po prikladnoy botanike i selektsii*, 1926, tom 16, vyp. 2 (in Russ.).
36. Ronzhina D.A., Rupyshev Yu.A., Ivanova L.A., Migalina S.V., Ivanov L.A. *Problemy botaniki Yuzhnoy Sibiri i Mongolii*, 2022, 21(2): 171-174 (doi: 10.14258/pbssm.2022077) (in Russ.).
37. Amelin A.V., Fesenko A.N., Zaikin V.V. *Vestnik OrelGAU*, 2015, 6(57): 18-22 (doi: 10.15217/issn1990-3618.2015.6.18) (in Russ.).
38. Amelin A.V., Fesenko A.N., Zaikin V.V., Chekalin E.I., Ikusov R.A. Transpiration activity of leaves in buckwheat varieties of different breeding periods. *BIO Web of Conferences*, 2022, 47: 01002 (doi: 10.1051/bioconf/20224701002).