AGRICULTURAL BIOLOGY,
2017, V. 52, № 3, pp. 429-436
(SEL'SKOKHOZYAISTVENNAYA BIOLOGIYA)

ISSN 2412-0324 (English ed. Online)
ISSN 0131-6397 (Russian ed. Print)
ISSN 2313-4836 (Russian ed. Online)

Agrophysical Research Institute: from basic physics towards practical plant growing (1932-2017)

UDC 631/635:631.58:551.5:57.087

doi: 10.15389/agrobiology.2017.3.429rus
doi: 10.15389/agrobiology.2017.3.429eng

AGROPHYSICAL, GENETIC AND BREEDING ASPECTS OF AGROBIOCENOTIC CONTROL IN AGRONOMY

(towards 85 Anniversary of Agrophysical Research Institute, Russia)

I.B. USKOV, V.P. YAKUSHEV, Yu.V. CHESNOKOV

Agrophysical Research Institute, Federal Agency of Scientific Organizations, 14, Grazhdanskii prosp., St. Petersburg, 195220 Russia, e-mail yuv_chesnokov@agrophys.ru (corresponding author)
ORCID:
Uskov I.B. orcid.org/0000-0003-2990-978x
Chesnokov Yu.V. orcid.org/0000-0002-1134-0292
Yakushev V.P. orcid.org/0000-0002-0013-0484
The authors declare no conflict of interests
Acknowledgements:
Supported in part by grant from Russian Foundation for Basic Research (№ 16-04-00311-a).
Received March 28, 2017

Abstract

This overview dedicated to 85 anniversary of Agrophysical Research Institute gives a retrospective of agrophysics formation as a specific research field covering investigation of physical, agronomical and biological factors to control agroecological systems. The article describes achievement in physics, mathematics, biology and pedology that ensured transition from a descriptive agronomy to the agronomy based on evaluation of the factors essential for plant grow and development, on plant productivity calculation, and on managing productivity of crops by special agrotechnologies. The development of IT communication and precision agricultural technics equipped with detectors of global targeting system, specific sensors and software, as well as the use of geographic information systems led to a new conception of plant yield control, i.e. a precision agriculture. Our researches are focused on computer-aided design and realization of precise agrotechnologies in field conditions. Further progress in plant growing seems to be due to modern genetic and breeding allowing to improve precision agriculture both for populations and individual plants influenced by different ecogeographic conditions. Recent approaches in genetics can speed up breeding new varieties for specific use in precision agriculture. In two experiments which differed only in temperature and illumination regimes under invariability of other parameters, 99 QTL determining 30 agronomically important traits have been identified in spring soft wheat. According to QTL mapping and ANOVA, changes in the temperature and illumination regimes did not influence 21 of 30 studied traits, which remained stable in manifestation. Only nine traits varied under tested conditions, indicating their manifestation to depend on these environmental factors. Elucidation of the QTL effects allows further analysis of the identified correlations and interaction between QTL and environment under natural conditions. In turn, these data allow to provide expression of certain genetic determinants which control physiological basis for economically valuable traits in specific ecogeographic conditions.

Keywords: agrophysics, physics of soil, pedology, precision agriculture, factors of plant growth, physiology and biochemistry of productivity, breeding and genetic analysis

At the end of the 19th century, the founders of Russian agrophysics were outstanding plant growers, soil scientists, agronomists and climatologists K.A. Timiryazev, V.R. Williams, V.V. Dokuchaev, P.A. Kostychev, A.A. Izmailsky, A.G. Doyarenko, A.I. Voeikov and N.I. Vavilov; they first defines agrophysics as the study of physical factors in plant life [1]. A.F. Ioffe started agrophysical research in 1930-1931 at the Physical-Technical Institute of the USSR Academy of Sciences, which coincided in time with founding research institutes by N.I. Vavilov, the president of the Soviet Academy of Agricultural Sciences, and corresponded to his ideas about the role of climatic and physical factors in formation of the properties and productivity of species. N.I. Vavilov supported the proposal of

A.F. Ioffe. By the decision of the Board of the People's Commissariat of Agriculture of the USSR (January 5, 1932) and the Presidium of the Academy of Agricultural Sciences No. 89 (January 7, 1932), the Physico-Agronomical Institute (FAI), now the Agrophysical Research Institute (API), was founded.

Scientific principles and retrospective. According to A.F. Ioffe, the first director of the API, agrophysical studies must transform agronomy from descriptive discipline into the practices and technologies of managing production process in the fields based on measurements and calculations. The problems he has formulated [2] are so fundamental that they remain strategic milestones of modern agrophysics. It was determined that it is necessary to group the factors affecting agroecological systems into five blocks: light, thermal, moisture, atmospheric and soil in correlation with plant cenosis. Modern trends include studying (i) the fundamental functioning patterns of agroecological systems; (ii) the development of bases, methods and tools, including information ones, for studying physical, physicochemical, biological, and biophysical processes in soil—plant—active layer of the atmosphere and managing the productivity of agroecological systems (sustainable farming and crop production under natural and regulated conditions); (iii) creation of simulation mathematical models of processes and technical means of collecting information on the state of plants and their habitats under continuous stochastic variability [1].

Among those worked at the API in the 1930s, there were N.A. Maksimov, the founder of ecological plant physiology, physicists D.L. Talmud and P.P. Kobeko, biophysicist G.M. Frank, soil scientists F.E. Kolyasev and P.V. Vershinin, and plant physiologist V.P. Malchevsky.

In the API laboratory of light physiology established by N.A. Maksimov the energy and regulatory function of light was studied using electric lighting. V.P. Malchevsky showed the influence of illumination on anatomy, biochemical composition, early ripening and productivity in more than 50 plant species and possibility of harvesting several times per year. D.A. Fedorov and V.A. Carfunkel substantiated the use of acetyl cellulose layer instead of glass coatings in greenhouses. B.S. Moshkov, who headed the laboratory of light physiology and light culture from 1945 to 1988, established a scientific school to study the physiological mechanisms of photoperiodism (B.S. Moshkov, V.I. Razumov and M.Kh. Chailakhyan). B.S. Moshkov also discovered the physiological role of leaf as an organ that determines photoperiodicity, and for the first time proved that these reactions are involved in crop precocity, productivity and resistance to various effects. The study of artificial alternation of light and darkness, long-day and short-day photoperiods, the interruption of darkness by light of different spectral composition, and the replacement of darkness by infrared radiation made it possible to simulate the transition of long-day and short-day plants from growth to reproduction with regard to the role of phytochrome, biological clock, biochemical and other changes. Attention was paid to the localization of the perception of photoperiodic signals, the induction of vegetative and seed reproduction. The idea of a comprehensive function of the photoperiodic reaction turned out to be extremely fruitful [3]. In the 1980s, B.S. Moshkov proposed the concept of a juvenile period the feature of which is the independence of its duration from illumination and temperature. The practical result of light-physiological studies is the development of methods for controlling early maturity and productivity in light culture, greenhouses and open ground.

Biophysical and radiobiological approaches were used in the development of an apparatus for determining the resistance of plants to stresses by the intensity of thermally induced chemiluminescence. Electrophysiological analysis of plant tissue viability and molecular genetic evaluation of plant and seed po-

tential productivity were developed. X-ray express diagnostics of sufficiently/insufficiently filled and damaged seeds, radioactive irradiation of seeds [4], magnetic and electromagnetic treatment for increasing sowing quality and yielding were used (G.R. Rick, N.F. Batygin, M.V. Arkhipov, V.N. Savin, V.F. Nikolenko, E.E. Gak). V.G. Karmanov proposed non-invasive methods for the dynamic study of water movement in conducting vessels of stems, water entering the roots, respiration and photosynthesis rates, electrophysiological quantitative characteristics of organs with changing illumination, temperature, moisture supply, and mineral nutrition. This resulted in development of a system of plants phytomonitoring and management of environmental conditions involving a plant as a sensor (V.G. Karmanov, O.O. Lyalin, S.S. Radchenko, S.N. Meleshchenko). Several generations of the first domestic climatic chambers and phytotrons were equipped with devices for regulation of temperature, humidity, intensity and spectrum of the light flux, gas composition of air, etc. Various types of phytotrons were created for research, breeding and agrotechnological tasks.

Bio-cybernetic approaches developed at the API from the mid-1960s. The first computer center in the system of agricultural institutions was organized at the API, which served as a prototype of similar structures in the system of the Ministry of Agriculture of the USSR and Academy of Agricultural Sciences [5].

Resource-saving ways of growing crops on artificial root-inhabited environments, proposed by E.I. Ermakov, laid the foundations of an industrial environmentally safe intensive technology for year-round vegetables growing [1].

The soil with high porosity, large pore sizes and lower density more actively regulates physical and biological processes than microaggregate or structureless soils [6]. P.V. Vershinin, I.A. Romanov, O.A. Agafonov and T.N. Danilova showed that the use of surface active substances and artificial structure-forming agents, including polymeric ones, makes it possible to increase the moisture content of the root layer, the availability of soil moisture for plants, the water resistance of soil aggregates, enhance their hydrophilicity and mechanical strength, improve the water-physical characteristics of solonetzic soils and the illuvial horizon of podzolic soils, and other important soil characteristics. The theory of minimal soil cultivation was further developed in the 1960s-1980s by I.B. Revut and A.V. Sudakov who showed that it is possible to obtain sufficiently high yields while preserving soil, resources and energy consumption.

In soil hydrophysics, a quantitative theory of moisture flow, methods for estimating rate of its evaporation, condensation, transpiration, their regulation and water supply of plants were developed (S.V. Nerpin, B.N. Michurin, N.F. Bondarenko, A.M. Globus) [7]. Mechanisms of heat transfer, the role of mineralogical composition, density and soil moisture in the intensity of heat transfer were revealed in thermophysics [8]. Methods for studying the radiation and heat balance of the active surface have been developed, and methods for its regulation have been outlined. Creation of a heat balance analyzer for research and automation of irrigation (the computer version of the device uses a modern element base) was an important result. The devices for recording parameters of the surface air layer were proposed to control field microclimate (M.A. Kaganov, B.L. Shinderov, Yu.L. Rozenstock) [9].

Dynamic and basic models of agroecosystem productivity, the mathematical theory of population dynamics on genetic, age and sex structure, control of cultured unicellular organisms [11] were a result of the theory of energy and mass transfer processes in the soil—plant—atmosphere system [10].

In the following years, the agrotechnical methods of plant growing in the North [12], the use of translucent polymer materials for greenhouses [13], "physical fertilizers" [14], the technology of using semiconductor materials in measuring instruments, energy devices and refrigerators were developed [15]. Recently, new

research areas appear, such as biological restoration of soils polluted with poisonous organic substances [16, 17], development of theory of plant ontogeny calculation based on computational analogues [18, 19]. The liming of acidic soils [20] is associated with the optimization of mineral nutrition and the physical state of arable horizon. Creation of automated control systems for technological processes in plant growing and agriculture also remains among the main task.

Precision farming system. The knowledge of the climate factors enabling crop production in different zones, the methods for monitoring characteristics of plants and their habitats, and mathematical modeling allow optimized practice when growing plants in large areas. Professor A.F. Ioffe, the founder and first director of the API, was in fact the first in the world who suggested the concept of an "electronic agronomist" in the middle of the 20th century [2] and defined precision farming (PF) as a new cropping paradigm. Realization of this concept became possible due to modern IT-technologies. In PF, a field is considered as a set of homogeneous (quasi-homogeneous) areas with different indicators of fertility and/or the state of sowings. If the differences are agronomically significant, the treatments are appropriately differentiated. The local adjustment of the technological impact is controlled by the onboard computers of agricultural units. Precision increases with the use of geostatistical approaches, the GLONASS system, remote sensing of the Earth and other methods for estimating the intrafield variability.

Computer design and comparison of the efficiency technologies for different intensities in model experiments [21-23] became the basis of domestic PF systems. In 2005-2015, production tests confirmed their prospects for ensuring high (not less than 5-6 t/ha) yields of grain with an increased protein content, regardless of soil and climatic conditions. At the same time, the costs of agrochemicals and fertilizers decreased by 25-30 % with 35-60 % lower load on the environment, a 1.5-1.7-fold increase in the payback of fertilizers and plant protection products, and the economic effect amounted to 840-1460 rubles/ha [24].

PF necessitates intelligent systems to maintain agrotechnologies, including improved measuring complexes and software to predict and monitor soil parameters, weeds, diseases, pests, etc., and to regulate the consequences of the techniques used. This, in turn, requires further in-depth genetic study of yield formation, interactions of the genotype and the environment, and the varietal features at the modern level.

QTL analysis in agrophysical research and improvement of precision farming. Analysis of quantitative trait loci (QTL), which allows us to speed up the selection of targeted varieties for PF systems is one of the biological approaches that can expand the possibilities of PF at the level of both populations (i.e. for specific ecogeographic conditions) and a single plant.

Using QTL analysis, identified QTL may be mapped, cloned and introduced into desirable genotypes by traditional hybridization [25]. The locus determining fruit size of tomato plants is a classic example of QTL identification and the first case of cloning a chromosome fragment that determines a quantitative economically valuable trait in this species [26]. The identification and molecular genetic mapping of QTL for morphological and economically valuable traits in *Triticum aestivum* L. [27, 28] and *Brassica rapa* L. [29, 30] were carried out from 2005 to 2016 on experimental fields in different geographical locations (Leningrad, Moscow, Samara and Kirov regions, Republics of Dagestan and Adygea). QTL mapping performed for the first time at the API in 2012-2013 in agroecobiopolygon, made it possible to identify for the first time yje chromosome loci in spring soft wheat that determined the manifestation of economically valuable traits under controlled conditions.

The chambers of the agroecobiopolygon are protected against external impacts and equipped with the system of microclimate control and regulation, allowing year-round growing plants of different heights (the latter is especially important for agricultural crops), and the devices for remote and contact diagnosis of the physiological and morphobiological state of objects when growing in vegetation vessels or peat-filled shelves [31, 32]. In controlled conditions (preset contrast regimes for the investigated factors with the invariability of the remaining parameters), E.I. Ermakov et al. [31] and G.G. Panova et al. [32] revealed the inheritance of sprouting to stalk-shooting period and stalk-shooting to earing period in wheat at year-round cultivation, and clarified a number of theoretical positions on selection of genotypes by transgressive traits. A methodology was developed for creating wheat lines with parameters corresponding to zonal soil and climatic conditions [31, 32], and in the same way a sort of daikon Peterburgskii (http://reestr.gossort.com/reg/cultivar/14807) was obtained.

The precise QTL identification and localization under controlled environment is based on the character of genotype-environment interaction, regardless of uncontrolled external environmental variables stochastically affecting the manifestation of the studied, primarily quantitative, traits. It is important both for studying plant physiology and genetics and for the breeding practice [25, 33]. Breeders can use QTL analysis data only when the results are reproducible, which was observed for some detected QTL [25, 34]. If the QTL manifestation will depend on environmental conditions, then, for example, in the PF system [21-23], the breeder will be able to correct growing conditions of the plants in such a way that the necessary trait appears. It has been established experimentally [25] that such a dependence of QTL does not always appear. In this case, the QTL position in the linkage group is remained the same regardless of year conditions and geographic location, although the LOD (logarithm of odds) may vary. Mapping QTL in API agroecobiopolygon made it possible for the first time to establish loci that affect the traits under study, primarily productivity [34]. Similar work is needed both in pre-breeding study of genetic determinants to implement PF programs [21-23] and, generally, in genetic and breeding research [35, 36].

Often, low LOD are characteristic of stable QTL which contribution to trait variability typically makes 10-20 %. Probably, stable manifestation of productivity traits is associated with these QTL. In contrast, in QTL, determining variability under certain conditions, the LOD values are often high. QTL, controlling plant size and productivity are mainly located in several linkage groups. Thus, in two experiments under controlled conditions of agroecobiopolygon [34] which differed in the illumination regime (40±0.5 and 50±0.5 W/m^2 PAR) and temperature (24-25/19-20 °C and 28-29/23-24 °C for day and night, respectively), 99 QTL were identified which determined 30 different agronomically significant traits. Based on QTL analysis and single-factor variance analysis, it was found that only 9 out of 30 estimated traits depended on the variable factors. Both used methods of statistical analysis yielded complementary results. In each of the statistical approaches, the maximum likelihood criterion was used, and the statistical significance of the results was determined. The reliability of the relationship between the identified QTL and the polymorphism on one or another characteristic was evaluated using the threshold value of the likelihood ratio for logarithm of odds (LOD-score). The QTL analysis revealed the block structure of the *T. aestivum* genome. The percentage of phenotypic variability due to each of the identified QTL was determined, and it was shown which of the parents introduced one or another QTL allele. The molecular markers genetically linked with the identified QTL were established.

A detailed understanding of the QTL position effects (taking into ac-

count their stability in a specific ecological zone) creates prerequisites for analyzing the observed correlations between the appearance of some QTL and light-temperature regimes, and for establishing the QTL–environment interaction under natural conditions to ensure the expression of genetic determinants of valuable traits in specific ecological and geographical conditions. In addition, QTL for morphological and phenological traits, first identified in different soil and climatic conditions of Russia in the mapping populations of *T. aestivum* and *B. rapa*, can be used to establish the genetic nature of quantitative traits in higher plants and to find out genotype–environment interaction mechanisms in order to develop marker-assisted selection (MAS) methods [25, 33]. Chinese cabbage varieties Yuna, MEGGI, VITAVIR (http://reestr.gossort.com/reg/main/516) and turnip Palitra (http://reestr.gossort.com/reg/cultivar/21036) derived with these technologies, which accelerate selection 2-3 times, are a successful application of this approach.

Thus, the carried out agrophysical research is aimed at the introduction of physical and mathematical methods in agronomy, agriculture, crop production, and productivity management and the scientific provision of precise farming as one of the most actively developed areas of the agro-industrial complex. The development of genetic selection methods extends the possibilities of modern agrophysics and precision agricultural technologies. Here, prospects are associated with the accelerated breeding technologies to derive varieties of different eco-geographical adaptation.

REFERENCES

1. Uskov I.B. *Agrofizika ot A.F. Ioffe do nashikh dnei* [Agrophysics: since A.F. Ioffe to present days]. St. Petersburg, 2002 (in Russ.).
2. Ioffe A.F. *Fizika i sel'skoe khozyaistvo* [Physics and agriculture]. Moscow-Leningrad, 1955 (in Russ.).
3. Moshkov B.S. *Fotoperiodizm rastenii* [Photoperiodism in plants]. Moscow, 1961 (in Russ.).
4. Batygin N.F., Savin V.N. *Ispol'zovanie ioniziruyushchikh izluchenii v rastenievodstve* [Ionizing radiation in plant growing]. Leningrad, 1966 (in Russ.).
5. Poluektov R.A. *Materialy Mezhdunarodnoi nauchno-prakticheskoi konferentsii «Agrofizika XXI veka» (k 70-letiyu obrazovaniya Agrofizicheskogo instituta).* St. Petersburg, 2000: 223-227 (in Russ.).
6. Vershinin P.V. *Pochvennaya struktura i usloviya ee formirovaniya* [Soil structure and formation]. Moscow-Leningrad, 1958 (in Russ.).
7. Nerpin S.V., Chudnovskii A.F. *Fizika pochv* [Soil physics]. Moscow, 1967 (in Russ.).
8. Kurtener D.A., Uskov I.B. *Klimaticheskie faktory i teplovoi rezhim v otkrytom i zashchishchennom* grunte [Climatic factors and temperature in field conditions and greenhouses]. Leningrad, 1982 (in Russ.).
9. Kurtener D.A., Uskov I.B. *Upravlenie mikroklimatom sel'skokhozyaistvennykh polei* [Field microclimate control].Leningrad, 1988 (in Russ.).
10. Nerpin S.V., Chudnovskii A.F. *Energo- i massoobmen v sisteme rastenie—pochva—vozdukh* [Energy and mass transfer in plant—soil—air system]. Leningrad, 1975.
11. Poluektov R.A. *Dinamicheskie modeli agroekosistemy.* Leningrad, 1991 (in Russ.).
12. Moshkov B.S., Sudakov V.L., Klochkova M.P., Drozdov V.N., Fekhretdinov A.F. *Rossiiskaya sel'skokhozyaistvennaya nauka*, 1984, 4: 13-16 (in Russ.).
13. Kotovich I.N., Masaitis G.V., Pashchenko T.E. *Polimernye plenki dlya vyrashchivaniya i khraneniya plodov i ovoshchei.* [Polymer films for growing plants and storage of vegetables and fruits]. Moscow, 1985 (in Russ.).
14. Panova G.G., Ktitorova I.N., Skobeleva O.V., Sinjavina N.G., Charykov N.A., Semenov K.N. Impact of polyhydroxy fullerene (fullerol or fullerenol) on growth and biophysical characteristics of barley seedlings in favourable and stressful conditions. *Plant Growth Regul.*, 2016, 79: 309-317 (doi: 10.1007/s10725-015-0135-x).
15. Chudnovskii A.F., Shlimovich B.M. *Poluprovodnikovye pribory v sel'skom khozyaistve* [Semiconductor devices in agriculture]. Leningrad, 1970 (in Russ.).
16. Ermakov E.I., Panova G.G. *Rossiiskaya sel'skokhozyaistvennaya nauka*, 2000, 5: 18-21 (in Russ.).
17. Ermakov E.I., Panova G.G., Stepanova O.A. Strategy of biological reclamation of chemically polluted ecosystems. *Russian Journal of Ecology*, 2005, 36(3): 171-178 (doi: 10.1007/s11184-005-0056-4).
18. Poluektov R.A. *Vestnik rossiiskoi sel'skokhozyaistvennoi nauki*, 2002, 2: 25-28 (in Russ.).
19. Poluektov R.A., Zakharova E.T. Two approaches to the description of distribution keys in crop simulation models. *International Agrophysics (Lublin)*, 2000, 14: 99-104.
20. Yakushev V.P., Osipov A.I., Minnulin R.M., Voskresenskii S.V. *Agrofizika*,

2013, 2(10): 18-22 (in Russ.).
21. Yakushev V.P. *Na puti k tochnomu zemledeliyu* [Towards precision agriculture]. St. Petersburg, 2002 (in Russ.).
22. Yakushev V.P., Lekomtsev P.V., Petrushin A.F. *Informatsiya i kosmos*, 2014, 3: 50-56 (in Russ.).
23. Yakushev V.P., Konev A.V., Yakushev V.V. *Informatsiya i kosmos*, 2015, 3: 96-101 (in Russ.).
24. Yakushev V.P., Lekomtsev P.V., Pervak T.S., Voropaev V.V. *Agrofizika*, 2016, 1: 43-52 (in Russ.).
25. Kumar J., Gupta D.S., Gupta S., Dubey S., Gupta P., Kumar S. Quantitative trait loci from identification to exploitation for crop improvement. *Plant Cell Rep.*, 2017: 1-27 (doi: 10.1007/s00299-017-2127-y).
26. Frary A., Nesbitt T., Grandillo S., Knaap E., Cong B., Liu J., Meller J., Elber R., Alpert K.B., Tanksley S.D. *Fw2.2*: a quantitative trait locus key to the evolution of tomato fruit size. *Science*, 2000, 289: 85-88 (doi: 10.1126/science.289.5476.85).
27. Chesnokov Yu.V., Pochepnya N.V., Kozlenko L.V., Sitnikov M.N., Mitrofanova O.P., Syukov V.V., Kochetkov D.V., Lohwasser U., Börner A. Mapping of QTLs determining the expression of agronomically and economically valuable features in spring wheat (*Triticum aestivum* L.) grown in environmentally different Russian regions. *Russian Journal of Genetics: Applied Research*, 2013, 3(3): 209-221 (doi: 10.1134/S2079059713030039).
28. Batalova G.A., Rusakova I.I., Kocherina N.V., Lovasser U., Berner A., Chesnokov Yu.V. *Otsenka linii ITMI i kartirovanie QTL u yarovoi myagkoi pshenitsy (Triticum aestivum* L.) *v usloviyakh Severo-Vostoka Rossiiskoi Federatsii* [Spring wheat (*Triticum aestivum* L.) line ITMI estimation and QTL mapping in the north-east Russia]. Kirov, 2016 (in Russ.).
29. Artem'eva A.M., Volkova A.I., Kocherina N.V., Chesnokov Yu.V. *Izvestiya Sankt-Peterburgskogo gosudarstvennogo agrarnogo universiteta*, 2012, 27: 73-77 (in Russ.).
30. Artemyeva A.M., Solovjova A.E., Kocherina N.V., Berensen F.A., Rudneva E.N., Chesnokov Yu.V. Mapping of chromosome loci determined manifestation of morphological and biochemical traits of quality in *Brassica rapa* L. crops. *Russian Journal of Plant Physiology*, 2016, 63(2): 259-272 (doi: 10.1134/S1021443716020047).
31. Ermakov E.I., Makarova G.A., Nerusheva G.V. *Programmirovannoe poluchenie v reguliruemoi agroekosisteme transgressivnykh po sroku kolosheniya linii pshenitsy. Metodicheskie rekomendatsii* [Creation of transgressive wheat lines with programmed time of earing in a controlled agroecosystem]. St. Petersburg, 2002 (in Russ.).
32. Panova G.G., Dragavtsev V.A., Kanash E.V., Arkhipov M.V., Chernousov I.N. *Agrofizik*a, 2011, 1: 29-37 (in Russ.).
33. El-Soda M., Malosetti M., Zwaan B.J., Koornneef M., Aarts M.G. Genotype × environment interaction QTL mapping in plants: lessons from *Arabidopsis*. *Trends in Plant Science*, 2014, 19(6): 390-398 (doi: 10.1016/j.tplants.2014.01.001).
34. Chesnokov Yu.V., Mirskaya G.V., Kanash E.V., Kocherina N.V., Lohwasser U., Börner A. QTL mapping of bread wheat (*Triticum aestivum* L.) grown under controlled conditions of an agroecobiological testing ground. *Russian Journal of Plant Physiology*, 2017, 64(1): 55-68 (doi: 10.1134/S1021443716060029).
35. Zhuchenko A.A. *Adaptivnoe rastenievodstvo (ekologo-geneticheskie osnovy)* [Adaptive plant growing — ecogenetic bases]. Kishinev, 1990 (in Russ.).
36. Zhuchenko A.A. *Adaptivnoe rastenievodstvo (ekologo-geneticheskie osnovy). Teoriya i praktika* [Adaptive plant growing — ecogenetic bases. Fundamental and practical aspects]. Moscow, 2008 (in Russ.).