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90 YEARS OF AGROPHYSICAL INSTITUTE AS A HISTORY OF PRIORITY ACHIEVEMENTS IN RUSSIAN AND WORLD AGROPHYSICAL SCIENCE

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Abstract

The article described the main stages of the formation of the Agrophysical Research Institute over 90 years of its existence. Since its foundation in 1932 as part of the Lenin All-Russian Academy of Agricultural Sciences (VASKHNIL) at the initiative of Abram F. Ioffe and Nikolai I. Vavilov, the Agrophysical Institute focuses on establishing mechanisms of genotype—abiotic environment interaction in order to control the production process in agricultural plants both in the field and under controlled growing conditions. Accepting the ideas of N.I. Vavilov, A.F. Ioffe put forward the concept that the agrophysical science, relying on the achievements of physics, mathematics and biology, will ensure the transition from descriptive agronomy to agronomy based on measurements and calculations of factors of productivity, growth and development of plants and crops. This allows agricultural practitioners to manage crop formation and productivity. It is emphasized that the main objectives still are understanding the fundamentals of the functioning of agroecological systems and the development of scientific foundations, methods and means to research physical, physicochemical, biological and biophysical processes in soil—plant—active layer of the atmosphere. The research studies also aim at simulation mathematical models of these processes. The development of theoretical foundations, methods and tools for managing the productivity of agroecological systems for effective and sustainable agriculture and crop production in natural and regulated conditions are relevant. The development and creation of technical means of obtaining information about the state of plants and their habitats also are in focus. Nowadays, the Agrophysical Institute, as a leading research institute, implements scientific and technical programs and projects based on agronomic physics and related sciences, e.g., agroecology, soil science, genetics, biophysics and plant physiology, agroclimatology, computer science and computational mathematics, cybernetics and instrumentation. The Agrophysical Institute successfully develops new areas of research focused on the methods for effective management of the growth, development and productivity of crops through physical, physicochemical and other abiotic factors affecting the habitat of plants in order to modernize and intensify agriculture and the entire agro-industrial complex.

Keywords: agrophysics, development history, soil physics, soil science, precision farming, plant growth and development factors, crop productivity management

Agrophysical Research Institute (AFI) was founded in 1932 as part of the Lenin Academy of Agricultural Sciences of the USSR (VASKhNIL) on the initiative of academicians Abram F. Ioffe and Nikolai I. Vavilov for the development of a new branch of natural and agronomic sciences in those years, the agronomic physics. Its tasks included establishing the mechanisms of interaction between the genotype and abiotic environmental factors in order to control the production process of agricultural plants in field and controlled growing conditions.

In the scientific heritageof N.I. Vavilov's genotype-environment interaction took a central place in the formation of phenotypic and genotypic variability of economically valuable traits and formed the basis of the classical law of homological series in hereditary variability [1], the main value of which lies in its prognostic essence.

N.I. Vavilov repeatedly pointed out the presence of varietal and genotypic differences in agricultural plants in terms of ecological plasticity, as well as the need to study the nature of these differences and manage them with the help of abiotic environmental factors, primarily physical and physicochemical ones [2, 3]. That is why, as the President of VASKhNIL, he invited the physicist and outstanding organizer of science, Academician A.F. Ioffe (1880-1960), who, being director of the Physico-Technical Institute (PTI) of the USSR Academy of Sciences in 1930-1931, initiated agrophysical research at the PTI. This period coincided with the formation of institutions in the VASKhNIL system. In 1932 A.F. Ioffe created an institute that solves the urgent problem for agriculture of increasing crop yields by managing ecological-genetic and physiological-ecological processes of crop formation. Based on the ideas of N.I. Vavilov, A.F. Ioffe put forward the concept that agronomic physics (agrophysics), based on the achievements of physics, mathematics and biology, should ensure the transition from descriptive agronomy to a science based on measurements and calculations about abiotic factors that determine the productivity, growth and development of plants, and to the development of agricultural practices to control the production process and the formation of crops. For many decades, A.F. Ioffe improved the branch of agronomic science he created, which turned into an independent scientific direction.

Agrophysics studies the physical, physicochemical and biophysical processes in the system soil-plant-active layer of the atmosphere and the main laws of the production process, the physical characteristics of the components of the system and agricultural products. Scientific foundations, methods, technical and mathematical tools and agricultural practices are being developed for the rational use of natural resources, increasing the sustainability of agroecosystems, agriculture and crop production. This is a section of interdisciplinary agricultural science that studies the physical components and structural and functional patterns of their interaction, as well as the interaction of the genotype and the environment, the varietal diversity of crops in relation to agrocenoses and agrolandscapes with the aim of agroecological optimization of modern farming systems.

The results of agrophysical research are used not only in plant growing and agriculture, but also in other fundamental and applied areas, for example, in animal husbandry (by regulating the temperature in the barn, you can control the milk productivity of animals), microbiology (abiotic factors significantly affect the processes of interaction of soil microflora with the rhizosphere plants). Therefore, terminologically, the formulation "genotype-environment interaction" most fully reflects the subject of agrophysics as a branch of modern agricultural science.

The stages of the formation of this new field of knowledge, the priority achievements of the domestic agrophysical school, the prospects for the development of agrophysical science and the practical use of research results as the basis of high-tech agricultural technologies are associated with the history of the Agrophysical Institute and a galaxy of outstanding domestic scientists, the physicists and agrophysicists G.M. Frank, V.P. Malchevsky, S.V. Nerpina, F.E. Kolyaseva, B.S. Moshkova, N.F. Bondarenko, A.M. Globus, I.B. Revuta, A.F. Chudnovsky, I.B. Uskova, A.V. Kurtener, V.A. Semenov, V.P. Yakusheva, R.A. Poluektov and many others who made an invaluable contribution to the creation and development of the Agrophysical Institute.

Agrophysical Institute: creation and formation. The specifics of the territorial development of the quarter to the south of the Akademicheskaya metro station in the north-east of Leningrad (now St. Petersburg) on the left side of Nauki Avenue is to create a multidisciplinary educational and scientific complex, similar to Oxford (Oxford, UK) and California (Los Angeles, USA). Scientific and educational organizations are concentrated in this area. In the center of the complex is the Peter the Great St. Petersburg Polytechnic University around which the Ioffe Physico-Technical Institute RAS (PTI), Agrophysical (formerly Physical and Agronomic) Institute, Vedeneev All-Russian Research Institute of Hydraulic Engineering, AO Research Institute of Precision Mechanics, Central Research and Development Institute of Robotics and Technical Cybernetics, Institute of Direct Current, Institute of Cytology RAS, Voeikov Main Geophysical Observatory are located. These research institutes and educational institutions are interconnected in many ways. Joint developments and projects are carried out, scientific seminars, conferences and symposiums are held. Branches of university departments function at the institutes, students do internships and complete their theses in the laboratories of the institutes, graduates continue their studies in postgraduate studies at research institutes. Unique research stands become an inter-institutional experimental base.

Most of the research institutes were created in the 1930s on the initiative of the leading professors of the St. Petersburg Polytechnic University and with their direct participation. The Agrophysical Research Institute is the clearest example of such a link in scientific cooperation. A.F. Ioffe, the Director of the Physico-Technical Institute, who was also the dean of the Faculty of Physics and Mechanics of the Leningrad Polytechnic Institute, with the support of N.I. Vavilov took the initiative to create such an institute in the VASKhNIL system.

As a result, by the decision of the Board of the People's Commissariat of Agriculture of the USSR of January 5, 1932 and the protocol of the meeting of the All-Union Agricultural Academy of Agricultural Sciences Presidium of January 7, 1932, the Physico-Agronomic Research Institute (now AFI) was founded as part of the All-Union Agricultural Academy of Agricultural Sciences. The AFI was created using the technological base of the Physico-Technical Institute; employees of the Physico-Technical Institute and the Polytechnic Institute were involved in the work.

A.F. Ioffe formulated the initial theme of the institute's work, which corresponded to the problems that were relevant at that time. In the fundamental works of A.F. Ioffe [4-6] identified the main areas of research in this new branch of the natural sciences.

Agronomic physics as a science began to form at the end of the 18th century. In Russia, its founders were prominent agronomists, soil scientists and climatologists. The beginnings of the foundations of modern agrophysics were laid in the works of V.V. Dokuchaev, K.A. Timiryazev, P.A. Kostychev, A.A. Izmailsky, V.G. Rotmistrov, V.R. Williams, A.I. Voeikov and N.I. Vavilov. The term “agrophysics” was proposed by A.G. Doyarenko in relation to soil research. These scientists first drew attention to the importance of physical factors in plant life and formulated their comprehensive study as the main task of agronomic physics. Agrophysical research of that period was limited to field observations without rigorous physical experiment and mathematical analysis. Therefore, despite the outstanding achievements of the researchers of that time, they rarely managed to create complete, convincingly proven theories.

In 1930-1931 A.F. Ioffe at the suggestion of N.I. Vavilova took up the organization of agrophysical research at the Physicotechnical Institute of the USSR Academy of Sciences. After the establishment of the Institute of Physics and Agronomy, it was the employees of the Physicotechnical Institute who formed the core of the team of agrophysicists, who determined the main strategic scientific direction of their research as the control of the production process of plants based on measurements and calculations.

In subsequent years, a specific research methodology for agrophysics was developed. Firstly, it was focused on the control of biological processes at all stages of ontogeny through physical, biophysical, physicochemical effects directly on the control object and through the environment surrounding this object. Secondly, the basis of management decisions was the measurement of the parameters of the state of the system soil–plant–active layer of the atmosphere and its monitoring. Thirdly, the study of the processes of energy and mass transfer had to be carried out in the field and laboratory conditions on full-scale, laboratory physical and mathematical models. The institute has developed a specific approach to the creation of devices, which has become a distinctive feature of agrophysical instrumentation. Devices were developed from a laboratory sample that provides maximum completeness and accuracy of measurements of the physical process parameters but has low operational reliability to a serial device with an accuracy sufficient for managing this process in the field by technological personnel without special professional training.

Agrophysics, as a natural agricultural science, developed according to its own internal laws, however, each period of personal leadership of the scientific team of the institute brought new directions in addition to the main ones that were formulated by A.F. Ioffe and turned out to be so fundamental that all subsequent leaders steadily developed them.

API leaders. Doctor of Physical Sciences, Academician of the USSR Academy of Sciences A.F. Ioffe, as the first director of the institute and its scientific adviser, developed the methodology of the electronic agronomist between 1932 and 1960. Thanks to it, specific agrophysical instrumentation was developed, the use of semiconductors in agricultural instrumentation was created, information and measurement systems for obtaining, collecting and storing information were created, electronic computing tools were used to develop agronomic solutions when managing crop growing processes.

Doctor of Technical Sciences, Corresponding Member of VASKhNIL S.V. Nerpin, who led the AFI team from 1961 to 1975, focused research topics on the development of mathematical modeling methodology in the description, analysis and research of the production process of plants and energy and mass transfer in their habitat.

Under the leadership of Doctor of Technical Sciences, Academician of the Russian Academy of Agricultural Sciences N.F. Bondarenko, who held the position of director since 1975, the methodology of programmed harvesting using mathematical models of the production process of the main field crops, as well as mathematical statistics and probabilistic methods were developed. Research on this topic was carried out comprehensively by many laboratories of the institute with broad international cooperative participation (Bulgaria, Poland, Hungary, Czechoslovakia, and Germany). At the initiative of N.F. Bondarenko, the Special Design Bureau of the institute designed and created a system of instrumentation for information support of crop programming technologies. The yield programming methodology has been adopted by domestic and foreign agriculture and crop production.

In 1979-1996, the Institute was headed by Doctor of Physical and Mathematical Sciences, Corresponding Member of the Russian Academy of Sciences I.B. Uskov, who laid the foundations for new directions in agrophysics: the creation of a theory, methods and means of controlling the microclimate of fields and greenhouse complexes; development of agro-climatic research using probabilistic approaches and methods of mathematical statistics; development of theoretical foundations for wind erosion of soils and methods for calculating soil protection anti-erosion systems and agrotechnical measures; creation of methodology, principles and rules for applying the theory of similarity in agrophysics. In the 1970s, the institute intensified research on the adaptation of agriculture to observed and predicted weather instability.

Since 1996, the position of director of the AFI has been held by Doctor of Agricultural Sciences, Academician of the Russian Academy of Sciences V.P. Yakushev. Under him, research was intensified on the creation of computerized knowledge bases accumulated by agronomy, crop production, agrochemistry, agrophysics, agrobiology, agroclimatology, and necessary for the creation of automated complexes for the synthesis of agricultural technologies. Agrophysical adapters began to be developed for information support of crop growing technologies, carried out at the planned and predictive-operational time levels. Research has been launched on the scientific support of the principles for the implementation of innovative agricultural technologies of precision farming (PF), which has become the next stage in the development of the adaptive farming method, work to improve which continues at the institute.

For the first time in the world, the idea of precision farming was put forward by Academician A.F. Ioffe in the methodology of “electronic agronomist” developed by him. To implement it, A.F. Ioffe proposed to consider the community of plants in a field or in a greenhouse, their habitat and purposeful human activity as a single agroecological system that can be described in the language of mathematics and create conditions for choosing optimal agrotechnical solutions by analyzing quantitative estimates of the system's behavior under various conditions. With this approach, it becomes possible to predict the size of the crop that can be obtained in specific soil and climatic conditions on a given plot of land, evaluate the resources required for this, select ways to effectively manage crop formation, and also determine what changes the soil will undergo as a result of applying that or other technology.

This research ensured the transition from experimental and descriptive agricultural science to the identification of quantitative patterns and theoretical generalizations. The prerequisites were founded for the emergence of a qualitatively new methodology for managing agricultural technologies. Its main feature is the transition from intuitive decisions based only on the experience of the farmer to quantitatively based methods of managing technological processes using computers. This led to the emergence of a new scientific and practical direction — harvest programming.

The ongoing research on PF is largely a logical continuation of work on crop programming [7, 8]. The theory of PF can be considered as a natural continuation of the development of the theory of crop programming at a new stage of scientific and technological progress using information technologies, global navigation systems (GLONASS/GPS), geographic information systems (GIS) and the Internet. The fundamental difference between PF and crop programming is that the recommended solution obtained using computer calculations is automatically implemented taking into account intra-field differentiation in a given agricultural field. When programming yields, the final decision remained with the agronomist, and the differentiation of the norms of technological impact could be carried out only from field to field.

Since 2016, the Agrophysical Institute has been headed by Doctor of Biological Sciences, Corresponding Member of the Russian Academy of Sciences Yu.V. Chesnokov. He took an orientation towards the integration of systems of precision farming, soil science, agrometeorology and land reclamation with adaptive crop production. In fact, this integrative process was identified in the fundamental works of Academicians A.F. Ioffe and N.I. Vavilov and is the establishment and use of the mechanisms of genotype-environment interaction to control the production process of plants in modern conditions and at a new scientific and technological level.

The research currently being carried out at the AFI can be divided into two main areas. The first is the improvement of plant growing technologies to optimize the production process (such as the technology of differentiated application of fertilizers, ameliorants and other agrochemicals), including the assessment of the condition of plants and crops by remote methods. The second direction is the improvement of plants using innovative breeding and agrophysical technologies, as well as obtaining varieties that are superior to the existing crops in terms of yield and quality, resistant to soil and climatic conditions of cultivation regions, efficiently using natural resources (light, water, elements of mineral nutrition, etc.), responsive to the application of fertilizers, ameliorants and other agrochemicals. Within these areas, methods are also being developed based on digital non-invasive optical, x-ray and other agrophysical methods for monitoring the physiological state of plants and crops, as well as their accelerated phenotyping according to economically valuable traits, productivity and stress resistance to abiotic environmental factors. In addition, reclamation and soil-agricultural theories have been developed (especially in the field of physics, physical chemistry and biophysics of soils, including their water, gas regime and physical and mechanical properties), the theory and practice of chemical reclamation of acidic soils; research is being conducted on agroecological monitoring and finding ways to reduce the accumulation of toxic substances and elements in agricultural products; the scientific foundations of systems for the reproduction of soil fertility, the use of fertilizers, crop rotations, and tillage are being developed; research is being carried out on the creation of working bodies of drainage-flushing machines for closed tubular drainage and the preparation of regulatory documents for field reclamation and other areas of research work.

Further development of scientific areas. Research by Professor F.E. Kolyasev (1898-1958) contributed greatly to the beginning of the development of agricultural theory in agrophysics. In his works [9, 10] the techniques and methods for managing the water balance of soils in various soil-climatic zones of the country are considered, and the theory of differential soil moisture is developed.

The works of Professor P.V. Vershinin (1909-1978) [11, 12], which covered the theoretical and practical issues of soil structuring, the use of chemical structure formers, including for protection against erosion, were important in creating the theory and methods of soil structure management. Academician E.I. Ermakov (1929-2006) made a significant contribution to the development of the theoretical foundations of the soil-forming process in the system of plant-soil complex. Thanks to the scientific school of Professor I.B. Revut (1909-1978) laid the agro-ecological foundations of soil cultivation for the soil-climatic zones of the country, and soil physics was introduced into agriculture [13-15].

Corresponding Member of VASKhNIL S.V. Nerpin (1915-1993) created two directions in agrophysical soil science: soil hydromechanics and theoretical physicochemical soil mechanics. His monographs [16, 17], in which the theory and methods of field water regime management are developed, have no analogues in the world scientific literature. The fundamental works of Professor A.M. Globus (1930-2008) [18, 19] actually laid the foundation for research in soil hydrophysics.

Professor M.K. Melnikova (1901-1986), head of the first radiochemical laboratory in Russia, was the initiator of extensive research on the physical chemistry of soils and the founder of the study of the behavior of uranium and plutonium fission products in soil. In her studies [20, 21] the method of isotope tracers in soil science was developed for the first time. Prof. Yu.A. Kokotov made a notable contributions to the theory of ion exchange in soils, including soil acidity, [22-24]. Professor N.F. Batygin (1928-2000) created the theoretical basis for the agrophysical trend in Russian radiobiology [25].

In 1928, a sector of agroclimatology was organized at the State Institute of Experimental Agronomy. In 1932, research on agro- and microclimatology for agro-climatic zoning and assessment of climatic resources in agricultural production was launched at the Voeikov Main Geophysical Observatory, but in August 1935 this work was stopped. At that time, simiar investigations began in the AFI, where research was focused on the analysis of the physical processes that form the microclimate of fields and crops, in contrast to the geographical climatic approach adopted in the Voeikov Main Geophysical Observatory.

Professor A.F. Chudnovsky (1910-1985) [26-28], an associate and follower of A.F. Ioffe, in the monographs [26-28] developed a theory and methods for controlling the thermal regime of soils. Already the first issue of scientific works of the Agrophysical Institute in 1935, included articles on the thermal and water regimes of soils by B.P. Aleksandrov, A.V. Kurtener, and N.N. Banasevich. The third issue published in 1941, contained a section entitled "Microclimate Issues"". The monographs of professors D.A. Kurtener and I.B. Uskov were devoted to the development of the theory of agroclimatology and its practical aspects [29, 30]).

The beginning of research in the field of ecological physiology of plants was the world-famous monograph "Physiological basis of drought resistance of plants" [31] by one of the first plant physiologists of the API, Academician N.A. Maksimov (1880-1952). Professor V.P. Malchevsky (1906-1942) developed methods of light culture and light stimulation in greenhouses and indoors with artificial light sources, he proposed light stimulation of seeds of seedlings to increase the intensity of photosynthesis and reduce the growing season. Works by V.P. Malchevsky made a significant contribution to the creation of the foundations of the theory of light physiology and light culture of plants.

The term "biocybernetics of plants" and the ideology of this approach were proposed by V.G. Karmanov (1913-1997) and developed as a science of cybernetic control of physiological processes in a plant. Phytomonitoring (S.S. Radchenko) and biophysical ideas about the processes of transport and energy exchange in a plant, including cell membranes (Professor O.O. Lyalin, 1932-1994) became a key element of biocybernetics. Based on the developments of V.G. Karmanov, the first vegetative lighting installation was created, after which new areas of research in light physiology began to develop at the institute and a series of domestic artificial climate vegetative installations was created. Proceedings [32-34] of the corresponding member of VASKhNIL B.S. Moshkov (1904-1997) gained worldwide fame and made a fundamental contribution to the theory of light physiology. They discovered the physiological role of the leaf as an organ that receives photoperiodic exposure. The phenomenon of photoperiodism made it possible to explain some regularities in the distribution of cultivated plants discovered by N.I. Vavilov. On the basis of photoperiodism, techniques have been developed to control the growth and development of plants. B.S. Moshkov showed in lighting installations the possibility of using light-periodism for pseudo-control of mutagenesis and the selection process under controlled conditions. On an in-depth genetic basis, research has been expanded to improve the efficiency of selection using the advantages that such an approach provides. The technology of growing plants in protected ground under electric lighting has been developed.

The methodology for creating perfect regulated large-scale agroecosystems, proposed by Academician of the Russian Academy of Agricultural Sciences E.I. Ermakov (1929-2006), based on the principles of physical modeling proposed by him. Such agroecosystems ensured the year-round production of high-quality plant products with a given biochemical composition [35]. Under the leadership of E.I. Ermakov, original vegetation and irradiation equipment, including a unique rhizotron technique for a two-dimensional root sphere were designed. On the basis of regulated agroecosystems, comprehensive studies of the evolutionary transformation of initially abiogenic substrates into soil-like bio-inert formations were carried out. The bases and methods of bioremediation of soils contaminated with liquid propellant components, oil and oil products have been developed. The genetic research on the programming of transgressions for plant breeding and introduction has been further developed. Works have begun, among other things, to study the water status of plants, their response to the action of increased doses of ultraviolet radiation and other abiotic stress factors of a physical and physico-chemical nature.

The Special Design Bureau of the Agrophysical Institute (Yu.P. Baryshnev) has developed and put into production a thematic series of original vegetative-climatic installations with controlled temperature, light and humidity conditions in a wide range of parameters. In 1982, these developments were awarded the State Prize of the USSR. For a long time, domestic phytotrons, physiological and selection-genetic laboratories were equipped with such installations.

The international expert community has recognized AFI as a leading scientific school that determines the formation of agrophysics as an independent branch of the natural sciences. Scientific organizations of a similar orientation were created in Bulgaria, Australia, Hungary, Switzerland and Germany. The famous Polish physicist Professor B. Dobzhansky (Bohdan Dobrzański, 1909-1987), after visiting the Leningrad Institute, achieved the creation in Lublin of the world-famous Institute of Agrophysics as part of the Polish Academy of Sciences.

An important stimulus for the creative cooperation of scientists was the publication of scientific papers of the API. The first issue was published in 1935 and was devoted to the problems of soil structure and the thermal regime of soils. Subsequent thematic collections were published annually (from one to five issues) until 1998.

The release of the international scientific journal on agronomic physics "International Agrophysics" was organized thanks to the community of scientists from Europe, Asia and America. The journal was published at the Department of Physics of the University of Agricultural Sciences (Budapest) and was first devoted to the study of the physical properties of soils and the quality of agricultural products. Since 1985, the publication of the journal was taken over by the Institute of Agrophysics of the Polish Academy of Sciences with the expansion of the scientific fields represented (physical aspects of the study of the environment and agricultural sciences).

Modern directions of scientific research in API. Proceedings of Academician N.F. Bondarenko (1928-2003) ensured the development of agrophysical scientific support and expanded practical application of the crop programming method. Based on these, information technologies for precision farming were developed [8].

With the development of branches of physics, geophysics, biophysics and plant physiology, mathematical physics and computational mathematics related to agrophysics, new areas of agrophysical research arose, focused on the development of methods of active intervention in the processes of growth and development of crops and management of these processes. These areas [36-40] include mathematical simulation of the production process of agricultural plants (R.A. Poluektov); development of the theory of similarity of agrophysical systems and processes (B.N. Michurin, A.M. Globus, I.B. Uskov, V.G. Onishchenko); analysis of the interaction of biological objects with physical fields of various nature — light, gravitational, magnetic, electromagnetic, acoustic, electrostatic (B.S. Moshkov, N.F. Batygin, N.F. Bondarenko, I.S. Lisker, V.N. Lazutin); creation and optimization of informatic technologies for managing the production process in agriculture and crop production (V.P. Yakushev, I.M. Mikhailenko); design and instrumentation of vegetation plants with controlled climate (V.G. Karmanov, A.F. Chudnovsky, Yu.P. Baryshnev); agrophysical instrumentation (I.P. Ananiev, Yu.I. Blokhin); development of coordinate precision farming as a modern continuation of the methodology of the "electronic agronomist" (V.P. Yakushev).

Climate change is becoming an increasingly important topic on the global agenda every year. In 2021, the management of carbon dioxide emissions was one of the most discussed issues in the world's highest ranking forums. Climate change forecasts from the world's leading institutions, obtained using many different models, are based on different options for the expected amount of CO_2 emissions. Such forecasts are systematized and evaluated by the Intergovernmental Panel on Climate Change (IPCC, Switzerland). The AFI Agroclimate Laboratory has proposed original methods for collecting and analyzing such forecasts, which, in combination with already available agrometeorological data, allows obtaining impartial estimates of probable climate changes based on fuzzy logic mathematics, easily adaptable for machine learning and analysis using artificial intelligence.

The observed climatic changes are accompanied by an increase in the frequency of occurrence of phenomena dangerous for crop production, which requires solving the problem of managing agro-climatic risks. AFI has developed software that allows processing large amounts of data on the existing and predicted agroclimate in combination with the measured agrochemical parameters of the soil and, on this basis, to make probabilistic forecasts of yields of the main crops that can be mapped for a specific user, taking into account the microclimate of the fields [41-45].

Precision farming (PF) is one of the areas of modern research work at the API, developed since 2002 under the guidance of Academician V.P. Yakushev [8], without exaggeration, can be called the world trend of adaptation of crop production to intra-field variability of crop formation conditions. Reasonable planning and subsequent differentiation of technological impacts in modern farming systems are directly dependent on the degree of intra-field heterogeneity [7]. The creation of reliable and accessible methods for detecting such heterogeneity, determining the degree of its intensity and spatial distribution in agricultural fields is a key task in managing crop production in the PF system.

A promising scalable resource for solving this problem is Earth remote sensing (ERS) data [8], the interpretation of which makes it possible to carry out a continuous continuous assessment of the state of crops and their habitat while simultaneously covering large areas. In Russia, with its large territory (and with the increasing availability of aerospace data), there is no alternative to such an approach in the information support of modern agriculture. Aerospace remote sensing data, ground-based measuring systems and mathematical models make it possible to significantly improve the quality and scale of information support for agriculture, monitoring of large natural objects and phenomena (land cadastres, forests, water bodies, fires, floods) [46].

AFI scientists led by V.P. Yakushev proposed two new methods of using remote sensing. The first involves the use of variogram analysis of satellite images, the second is based on a comprehensive assessment of the dynamics of changes in the optical indicators of reflection indices calculated from hyperspectral images. A basic algorithm has been developed for detecting and highlighting the boundaries of intra-field heterogeneity using hyperspectral images of agricultural fields and using optical criteria (reflection indices) that characterize specific and non-specific features of the spectral indicators of sowing under the influence of stressors. To implement the geostatistical approach, a toolkit was created and tested for constructing empirical variograms and their approximations based on remote sensing data, which functionally describe the statistical structure of spatially varying indicators of the state of the soil or sowing on an agricultural field. The prospect of automating this process has been studied. Semivariogram analysis is an effective method for characterizing the structure of data spatial variability. It is widely used to evaluate the spatial heterogeneity of surface reflectance values and improve image classification. It should be noted that the use of new methods of analysis and interpretation of satellite data would significantly increase the scale of information support for PF technologies.

In 2009-2017, the concept and theoretical basis for the management of agricultural technologies in precision agriculture was developed, which continues to be improved [47]. According to the proposed concept, the general task of managing agricultural technology includes four levels of tasks that are solved on different time scales. At the upper, 1st level, the problem of managing crop rotations on an annual scale is solved; on the 2nd, implemented on a daily scale at one vegetation interval, the task of program control; tasks of the 3rd and 4th levels are implemented in real time. At all levels, the object of management is the field with the sowing of agricultural crops. However, the concept does not take into account the fact that the agrocenosis, in addition to the main crop, includes annual and perennial weeds. They compete with the crop for moisture and nutrients, and crop losses from weed infestation can exceed 50%. Therefore, optimal technological programs throughout the growing season should include not only fertilization and irrigation operations, but also herbicide treatments. Such programs should be formed taking into account the fact that mineral nutrition stimulates the growth of both cultivated plants and weeds, and herbicides not only suppress the growth and development of weeds, but also act depressingly on cultivated plants.

The formation of a unified management program that takes into account the state of the main crop and weeds and includes the simultaneous application of mineral fertilizers and herbicide treatment makes it possible to avoid crop losses and excessive consumption of fertilizers. In addition, optimization of fertilizer doses that meet the biological needs of the crop in nutrients activates metabolic processes, accelerates herbicide inactivation and increases resistance to it. That is, due to a more intensive accumulation of organic mass, a growth decrease in the concentration of the herbicide in plant tissues occurs, and smaller amounts of the drug are inactivated faster with optimal metabolism. Optimal nutritional conditions also increase the overall biological competitiveness of the crop in relation to weeds. Therefore, the combined use of herbicides with mineral fertilizers is one of the effective methods of weed control in crops and a significant increase in crop yields. To implement such an idea, a significant refinement of the concept and theory of management of agricultural technologies was required: new mathematical models of agrocenosis, optimality criteria and algorithms for the formation of control programs were proposed. Fundamentally different robotic technological machines will also be needed, which will significantly speed up the process of crop management.

The currently observed extreme manifestations of weather conditions can lead to an imbalance in such ecological functions of the soil–plant–active layer of the atmosphere system as biogeochemical circulation, energy and moisture exchange, accumulation, transport and removal of nutrients, buffer capacity. There are uncertainties in accurately assessing the conditions of sustainability (ability to resist impacts) and recovery (speed and degree of return to the original dynamic equilibrium) of the balance of these ecological functions of the specified system. Therefore, a holistic analysis of the state of the system before and after impacts should be based on the results of interdisciplinary related studies (48).

Improving the methodology for studying the stability and restoration of the soil–plant–active layer of the atmosphere system after natural and anthropogenic impacts in the API is carried out in three related interdisciplinary areas.

As part of the first direction, instrumental studies of physical (density, aggregate composition), physicochemical (pH), hydrophysical (moisture content, main hydrophysical characteristic, moisture conductivity) and, in the future, thermophysical (temperature, thermal conductivity, heat capacity, thermal diffusivity) properties of soils are carried out [49-51]. The results obtained are necessary for analyzing the close relationship between soil properties in assessing their stability and recovery after natural and anthropogenic impacts.

The second direction includes instrumental analysis of carbon and nitrogen cycles, which are fundamental interdependent processes in the global biogeochemical cycle of substances in ecosystems. Modern studies are aimed at conjugated assessment of the degree of interrelationships between carbon and nitrogen cycles in various climatic conditions with the dynamics of temperature, moisture and oxygen content, available nitrogen and carbon compounds, microbiological and enzymatic activity, mainly in the uppermost part of the soil genetic profile. First, instrumental studies generally involve an analysis of the influence of natural and anthropogenic impacts on the sequestration of organic matter in soils and their clay fractions [52, 53]. The intensity of sequestration and the degree of carbon fixation in the genetic profiles of soils are largely determined by the amount and mineralogical composition of their clay fraction, the content of iron hydroxide under various redox, hydrophysical, thermophysical, biochemical, and microbiological conditions. That is why, in order to improve the methodology, it is necessary to deepen knowledge about the fundamental mechanisms of carbon sequestration in soils as a result of interactions of nonspecific (carbohydrates, lignin, lipids, phenols, amino acids) and specific (humic acids) organic compounds with primary and secondary clay minerals in soil genetic profiles in order to assessment of the significance of these mechanisms in maintaining sustainability and restoring the balance of the carbon cycle. Secondly, the modern study of carbon and nitrogen cycles in various land use systems is mainly devoted to the analysis of the influence of soil properties on the microbiological processes of the formation of carbon dioxide (CO_2) and nitrous oxide (N_2O) in them, as well as on the intrasoil and direct fluxes of these substances from soils [54-56]. A quantitative assessment is required of the conditions for the formation of dominant processes of organic matter mineralization, autotrophic and heterotrophic respiration, nitrification and denitrification in the profiles of various soils, the predominant ways of transport of CO_2 and N_2O in soil profiles, the contribution of intraprofile transport of CO_2 and N_2O to their direct emissions from soils, as well as the role the aforementioned managed processes in maintaining sustainability and restoring the balance of carbon and nitrogen cycles.

Within the framework of the third line of research, an analysis is made of the closeness of the relationships between the meteorological parameters of the surface layer of the atmosphere, as well as the components of the heat and water balance of the underlying surface, and the hydrophysical and thermophysical properties of soils (57-59). Improving the methodology involves a more correct description of latent and explicit heat and moisture fluxes between the stratified ground air layer and a rough underlying surface, a deeper analysis of the mechanisms of transport of heat fluxes, capillary and film moisture in the genetic horizons of soils, a reasonable analysis of the degree of relationship between heat and moisture fluxes in soil and from the underlying surface in order to accurately assess their conjugated contribution to achieving the required stability conditions and restoring the soil—plant—active layer interaction.

The Agrophysical Institute continues research on topical issues of field experiment methodology, agroecological monitoring, management of effective soil fertility, phytosanitary condition and productivity of agrocenoses. For example, a multilevel system of field experiments has been created in the Menkovsky branch of the AFI, which serves as a methodological basis for large-scale fundamental and applied research [60]. Thanks to it, using new methodological approaches, the fundamental and applied foundations of precise crop fertilization systems [61, 62], the methodology of phytosanitary monitoring and applied aspects of precision integrated plant protection [63, 64] were significantly developed, theoretical aspects of the interaction of ameliorants with soil were developed, and adaptation problems were studied. , agro-ecological and agro-economic aspects of melioration and cultivation of soddy-podzolic soils, including those on re-developed agricultural lands [60, 62, 65].

Special attention in the API is given to land reclamation as one of the ways to adapt Russian agricultural production to climate change, which can significantly affect the agrophysics and physical chemistry of soils, in particular, their water permeability. Thus, the increase in temperature in winter significantly reduced the depth of soil freezing in the Nonchernozem zone of Russia (on average from 100-120 to 45-70 cm) and, as a result, limited the cryogenic restoration of the vertical pore space, which plays an important role in the formation of the total water permeability of the soil stratum [66]. This fact had a significant impact on the efficiency of closed drainage systems. Its negative consequences are observed when drains are drained from fields drained by closed tubular drainage during heavy rainfall. In this regard, in recent years, the Agrophysical Institute has begun studying the restoring of closed tubular drainage with an expired service life and siltation of more than 80% of the tubular drain cross section. Theoretical studies of the processes of destruction and transportation of silt deposits in the tubular cavity of the drain to its mouth, tested on models and on a specially designed research stand, made it possible to establish the manufacture of milling working bodies of drainage flushing machines intended for operation during the restoration of a faulty drainage tubular drainage [67]. In addition, scientific and practical guidance has been issued to reduce the risks of growing crops on drained reclaimed land in a changing climate [68)]. Comprehensive tests have been carried out and regulations for the production, use and technical conditions for more than two dozen ameliorants and fertilizer materials have been developed. In Russia, liming of more than 70% of acidic soils is carried out using the regulatory and technical documentation developed at the Agrophysical Institute.

Using remote sensing methods, reclaimed lands were surveyed and the technical condition of drainage systems was determined. The developments of the Agrophysical Institute on the assessment of agricultural melioration facilities using unmanned aerial vehicles have found application in the design, repair and construction of such facilities (69).

Modern research on plant light physiology and bioproductivity of agroecosystems is focused on understanding the patterns of interaction between plants and associated biota and habitat in a regulated agroecosystem when modeling optimal and stressful conditions, as well as on developing methods and means to increase plant resistance to stress factors and obtain stable high yields of the required quality in conditions of protected and open ground [70, 71].

Particular attention is paid to the genetic breeding methodology for increasing the productivity and resistance of agricultural crops to the ecological-geographical and landscape-climatic conditions of the growing regions, obtaining new forms with a predictable set of economically valuable properties, taking into account the specifics of the genotype-environment interaction [72, 73].

For decades, the API has been developing highly efficient resource-saving phytobiotechnologies and original light-irradiating equipment for year-round intensive production of plant products with specified quality and functional characteristics [71, 74]. Systems for rapid assessment of the physiological state of vegetative plants and the quality of seed material were tested using information-measuring means of phytomonitoring, optical and radiographic methods [75-77].

Continued study of the mechanisms of genotype-environment interaction under controlled conditions will deepen our understanding of the fundamental principles of controlling the production process of plants and regulating the flow of biogenic elements in agroecosystems. These data will also be used to create plant forms that are highly valuable in terms of productivity and quality, obtained using the original genetic breeding methodology, next-generation bio-, nano-, agrotechnologies and applied digitalization [71, 78-80]. Among the immediate scientific and practical tasks, there are optimization of production process in intensive light culture and the creation of high-tech automated autonomous stationary and mobile phytotechnological complexes with original vegetation-and-irradiation equipment and resource-saving agricultural technologies for continuous year-round production of plant products with specified functional and quality characteristics in the immediate vicinity to the consumer, regardless of natural and climatic conditions [71, 81, 82]. Obtaining highly productive forms of plants (including marker-assisted selection, MAS) [83-85], intended for intensive light culture, is an essential element of the proposed original effective interdisciplinary methodology and technologies for the formation of plant products and raw materials with specified qualitative and quantitative characteristics [71, 86].

Another promising scientific direction is the practical use of microorganisms. In particular, microorganisms that simultaneously produce monooxygenase and hydrolytic cellulases are of interest for the conversion of plant residues and the regeneration of spent organomineral substrates [79, 87]. The API develops the fundamental principles for the participation of microorganisms in the generation of electricity in the plant-microorganisms-rhzosphere system [80, 88]. When creating biopreparations with a complex action, the peculiarities of the secretion of microbial exometabolites and their influence on the production process of agricultural crops under favorable and stressful conditions are taken into account [71].

The basis of integrative interdisciplinary studies of the genotype-environment interaction will be i) the digital methodology for monitoring the production process (including PF) [8, 89-91] and the quality of seed material; ii) diagnosing and assessing the state of fields using remote sensing methods and predicting crop productivity [46, 92, 93]; iii) determination of plant tolerance and adaptability to abiotic stressors using non-invasive optical, X-ray and other physical methods of analysis and digitalization [75-77].

International scientific cooperation. Many agrophysicists and organizers of science from the Baltic countries, Transcaucasia, Central Asia, China, Vietnam, Eastern and Western Europe began their scientific career at AFI. The Agrophysical Institute has strong ties with leading research centers and universities in Poland, Germany, Hungary, Moldova, Belarus, Slovakia, the Czech Republic and other countries.

Thus, in the framework of scientific cooperation with the Slovak Agricultural University (Slovenská poľnohospodárska univerzita — Slovak University of Agriculture, SUA, Nitra, Slovakia), Russian and Slovak scientists carried out joint studies of energy and mass transfer processes in the soil–plant–atmosphere system. It is shown that the use of biochar provides many advantages to agriculture by improving the whole range of soil properties, including its structure. However, various effects of biochar exposure depend on its physical and chemical properties, application rates, initial soil properties, etc. The field trials were carried out in 2017-2019 with Haplic Luvisol biochar at the SUA experimental station. Initial as well as repeated application of biochar resulted in improved soil structure. Increasing soil organic matter from initial and reintroduced biochar significantly maintained the stability of soil aggregates, while humic-based organic matter did not provide such stability [52, 57].

Scientific and technical cooperation is developing with TOO Baraev Scientific and Production Center for Grain Farming (Akmola region, Republic of Kazakhstan) on the effective use of software, hardware and technical systems in agricultural production. At a specialized experimental site in the Republic of Kazakhstan, the prospects for using the precision farming system developed at AFI were evaluated. On its basis, a new algorithm is proposed that uses remote sensing data and ground measurements, which allows you to move from inefficient monitoring activities and a static assessment of the observed phenomena to precision control methods and the prompt use of crop correction tools that increase the productivity of spring soft wheat. In addition, according to the dynamics of changes in agrolandscape field conditions determined by the terrain, it was possible to describe the distribution of watercourses that characterized the reserve of productive moisture in one or another part of the field [94, 95].

The Agrophysical Institute and the Center for the Study of Agricultural Landscapes (The Leibniz Center for Agricultural Landscape Research, ZALF, Müncheberg, Germany) conduct joint research on the creation and use of dynamic models of the production process of agricultural plants in applied and theoretical problems of agroecology. Thus, the API proposed an integrated system for modeling the production process of agricultural crops, which is applicable for the analysis of agricultural technologies, in particular, alternative strategies for planning crop rotations in various farming systems. It has been shown that the processes of flowering and seed maturation in plants, as a rule, are better modeled by the median of the ensemble of models than by the average of the ensemble and individual models. The yield is more accurately estimated not by an ensemble of models, but by the best models. Higher accuracy is usually achieved for spring crops, best results are obtained for maize for silage, and the lowest performance (in terms of agreement index) was noted for winter rapeseed. It has been established that only models with reasonable accuracy (i.e., without failures) for all crops in the target environment should be selected for crop rotation. In general, the use of the developed ensemble of crop models is one of the ways to improve the accuracy of forecasts, but relatively low variability of the output of the ensemble is possible, which indicates the variogram of the studied fields for different types of cultivated crops [96].

Since 2016, the Agrophysical Institute has been participating in the work of the ISTA technical committee (Advanced Technologies Committee, International Seed Testing Association, Wallisellen, Switzerland) on new technologies for assessing the quality of seed material. In 2022, at the 33rd ISTA International Congress (Cairo, Egypt), API presented a report "Software for processing and analysis of digital X-ray images of seeds" (https://www.seed-test.org/api /rm/R4G8AC7KS6QARNA/4-software-for-processing-and-analysis-of-digital.pdf), covering a number of API developments. These are software for improving the quality of initial digital X-ray images of seeds, VideoTesT-Morphology software for automatic analysis digital x-ray images of seeds, software Passport-Zerno for automatic recognition of the main types of hidden defects in seeds of grain crops, e.g., wheat, barley, rice, rye). Also, the Russian GOST R 59603-2021 "Crop Seeds. Methods of digital radiography" was announced. The presented inventions will further allow harmonizing the specified national standard with the current ISTA Rules in terms of X-ray analysis of seeds. Previously, approaches to seed radiography proposed in the API were reflected in publications in Russian and foreign scientific journals [97, 98].

The cooperation of scientists from the Agrophysical Institute with colleagues from the Leibniz-Institute for Plant Genetics and Crop Research (Leibniz-Institut für Pflanzengenetik und Kulturpflanzenforschung, Gathersleben, Germany) is one of the longest and largest. A number of studies have been carried out to establish the ecological and genetic mechanisms of genotype-environment interaction, in particular, to identify and identify genes and chromosome loci that determine economically valuable traits in spring common wheat. As a result, Russian and German partners have identified QTL (quantitative trait loci) which determine of more than 40 economically valuable traits in the conditions of the agroecobiological polygon [99]. The QTL of diffuse leaf reflectance indices have been mapped [75], and associative mapping and genome-wide study of chromosome loci and genes that determine the trait of frost resistance in spring common wheat (*Triticum aestivum* L.) were carried out [100-102]. In addition, in collaboration with colleagues from the Institute of Agricultural Microbiology (St. Petersburg-Pushkin, Russia) and the CSIR — National Botanical Research Institute (Lucknow, India), resistance to the highly toxic nickel metal was studied in T. aestivum in the interaction of plants with rhizobacteria and the stages of rhizobial defense mechanisms in plant-bacterial associations under nickel stress were determined [103]. It has been shown that both partners (plant and bacteria) are able to reduce nickel toxicity and have developed different mechanisms and strategies that manifest themselves in plant-bacterial associations. In addition to physical barriers such as plant cell walls, thick cuticles, and trichomes that reduce abnormal nickel intake, plants reduce nickel toxicity using their own antioxidant defense mechanisms, including enzymes and other antioxidants. Bacteria, in turn, effectively protect plants from nickel stress and can enhance phytoremediation [104, 105].

Thus, over the 90-year history, the Agrophysical Institute founded on the initiative of Academicians A.F. Ioffe and N.I. Vavilov has gained wide international recognition. The main research are focused on fundamental functions of agroecological systems, on development of scientific foundations, methods and means for studying physical, physico-chemical, biological and biophysical processes in the soil—plant—active layer of the atmosphere, on creation of simulation mathematical models of these processes. The development of theoretical foundations, methods and tools for managing the productivity of agroecological systems are carried out in order to increase the efficiency and sustainability of agriculture and crop production in natural and regulated conditions. Technical means are being developed to obtain information about the state of plants and their habitats. The research uses methodological approaches of agronomic physics and related sciences, i.e., agroecology, soil science, genetics, biophysics and plant physiology, agroclimatology, informatics, computational mathematics, cybernetics and instrumentation. Innovative research area that is successfully developing includes methods for effective management of crop growth, development and productivity through the influence of physical, physico-chemical and other abiotic factors on the plant habitat.

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