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RESERVES OF AGRO-TECHNOLOGIES AND BREEDING FOR CEREAL YIELD INCREASING IN THE RUSSIAN FEDERATION

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Abstract

The authors consider new approaches to cereal yield increasing by relevant agro-technologies and breeding methods. Earlier it was shown that the yield of agrophytocenosis is determined by seven genetic and physiological systems, the GPS (A.B. Dyakov and V.A. Dragavtsev, 1994), the breeders are de facto faced to increase the crop yield. There was the first genotyping of each GPS of productivity which showed the ways to optimal strategy of yield management via GPS. In this paper for the first time it is shown that effect of some systems can be increased both by agro-technological and breeding methods. In the future the agro-technologies should be improved by the development of precise agriculture. In this, it is necessary to provide i) monitoring of phytocenoses, ii) indication of limiting factors for each stage of ontogenesis which impact the traits starting their development, iii) development of new agro-methods precisely influencing the phytocenosis by biologicals which can level the negative effects of specific limiting factors. In other words, «phase-specific agro-technologies» must be developed to protect sensitive phases of plant ontogenesis. To obtain maximal effect from precise breeding technologies, it is necessary to create mathematic models allowing to estimate quantitatively haw each GPS contributes to yield increasing at each stage of ontogenesis. Moreover, these models should be further used both in classical field breeding and, most effectively, in special phytotron where the dynamics of environment limiting factors typical for the territory of interest can be simulated. On the base of first created models the important quantitative algorithms for breeders were suggested which provide rapid identification of individual genotypes by their phenotypes and optimal selection of the parents to predict and obtain the transgressions (for self-pollinated plants). In this paper it is shown that, though certain GPSs can be improved both by agro-technologies and breeding, there are some traits which can be changed only by breeding. Analysis of unique breeding results of V.S. Pustovoyt, P.P. Lukyanenko and Norman E. Borlaug showed the GPSs improved by these great breeders and those ones unimproved. Breeding and agro-technology programs for each GPS must result in further yield increase. The paper summarizes the perspectiveness of hormones used during different phases of ontogenesis to deepen roots into soil, to increase attraction and to improve stress tolerance. Agro-technologies and breeding technologies must work together, because the high genetic potential of newly bred varieties can not be realized with improper agro-technology, and, in contrary, the best agro-technology will be limited by low potency of the variety. Modern agro-physical equipment (in particular, special phytotron accelerating breeding process), IT-technologies, mathematical modeling used to control crop yields are the main factors for optimal teamwork of agro-technologists and breeders with the view of effective agriculture in Russia.

Keywords: agro-technologies, breeding, reserves of cereal yield increase in Russia.

Yet 100 years ago, the farmers of the world used the following levers to increase the gross output of crop production: plowing new land up; optimized location of genera, species and varieties of agricultural plants in macro, meso- and micro-ecological niches; improvement of agricultural technologies; breeding new varieties and hybrids using genetic breeding technology; creation of variety, species and genera mixes to maximize the use of environmental resources by complex agrophytocenoses. Currently, the first and second approaches have almost exhausted their possibilities. There are almost no new lands left, optimizing the placement of cultures on the territories has been finished in general (it was a long empirical process of «trial and error»), and just the system of variety zoning is continuously running. According to recent data, the ratio of contribution in the yield increase due to improved agricultural technologies and breeding technology development in the different zones of the Russian Federation is from 50 %:50 % to 30 %:70 %. Creation of variety, species and genera mixes is highly developed, for example, in Brazil, where up to 80 % of the area are seeded with genotype mixtures; in Russia, this approach is just beginning to develop, but it is experiencing difficulties due to the lack of new machinery modifications and special systems for monitoring and maintenance of complex agrophytocenoses.

A global crisis of agricultural production arose in the 21st century because technological intensification of crop production could not solve the problem of further yield increase but was associated with the growth of energy costs and ecological imbalance. Solving the problem of hunger and malnutrition of the growing population of the world and reduction of the negative impact on the biosphere are the two main problems of the contemporary agricultural sector. Therefore, identification of the reserves of inexpensive, environmentally safe and accurate agricultural technologies, as well as opportunities to radically improve crop breeding, is very important.

Priority Russian phenotyping (subdivision of the final yield into its seven contributions as a result of functioning seven genetic and physiological systems) and presented approaches to improve the efficiency of each system by agrotechnological and breeding methods for the first time demonstrate the quantitatively assessed significant potential for increasing crop yields in the Russian Federation.

New approaches to the estimation of reserves of agricultural technologies and breeding technology in solving problems of increasing yield. The effectiveness of the above five «arms» to increase yields has not been assessed in a rigorous manner so far. This can be assessed based on the currently available knowledge about the prospects of agricultural, genetic and breeding techniques which contribute in the yield improving.

A.B. D'yakov and V.A. Dragavtsev have shown [1] that the yield of agrophytocenosis is determined by the following genetic and physiological systems (GPS): Attraction (ATTR, System 1), or redistribution of photosynthesis products and elements of mineral nutrients from the stem and leaves to the centers of attraction, i.e. the ear (in cereals), the flower basket (in sunflower), etc.; microdistribution of attracted plastic substances (MIC, System 2) between the grains and the chaff in the wheat ear, between the seed core and peeling in sunflower, etc.; adaptability (AD, System 3) as total adaptation to the specific conditions of field and trials year, or specific adaptation in case of provocative background, such as drought, cold, heat, salinity, changes in soil pH, etc.; horizontal immunity (IMM, System 4) as a horizontal (polygenic) resistance to diseases and pests; «payment» by plant dry biomass for the limiting factor unit in soil nutrition (EFF, System 5), i.e. nitrogen, phosphorus, potassium, etc.; tolerance to thickening (TOL, System 6) as the ability to withstand a high density of planting and maintain a large number of ears per 1 m^2 of the area; genetic variability for the duration of ontogeny phases (ONT, System 6).

This experimentally tested approach described back in 1994 [1], in fact, has become the priority Russian phenotyping (phenotyping is a recently arisen line of research abroad that attempts to divide the final phenotype signs that formed during growth and get to the primary elements of productivity that are related more closely with the gene products than the resulting complex properties of productivity and yield) [2-6].

Domestic phenotyping appeared to be significantly more effective compared to foreign approaches [7, 8]. However, it contained no information on how to increase the efficiency of GPS based on agro- and/or breeding techniques.

Analysis and experiments have shown that the efficacy of the contribution in the yield of the systems 1, 2 and 3 can be increased by both agricultural and genetic breeding techniques, and of the systems 4, 5, 6 and 7 can be mainly increased by genetic breeding only.

What are the provisions to increase yield while improving the agricultural and breeding techniques? Let us consider the summary table of the cereal areas of the world, represented by S. Borojevic [9] in a special lecture at the International Congress of Genetics (Moscow, August 21-31, 1978).

Average and record productivity values in the agricultural production of the major cereal regions of the world [9]

Crop, production	Yield		Record to average value ratio
	average	record	
Corn, cwt/ha	44.4	189.4	4.3
Corn, cwt/ha	18.8	145.2	7.7
Wheat, cwt/ha	16.1	73.9	4.6
Sorghum, cwt/ha	18.6	197.4	7.1
Oat, cwt/ha	17.2	106.3	6.2
Barley, cwt/ha	20.4	114.1	5.6
Potato, cwt/ha	282.2	940.8	3.2
Sugar beet, cwt/ha	469.1	1,333.0	2,8
Milk (annual yield), kg/head	4,635	22,500	4.9
Chicken egg (1 laying hen), pieces/year	230	365	1.6

As is evident, the wheat and sorghum yield, in principle, can be increased by more than 7 times by improving agricultural technologies and genetic improvement of breeding assortment.

Prospects for the development of precision agrotechnologies and their possible contribution to improving yields. In 2007-2008, the precision farming technique saved about 20 % of fertilizer and ensured a 15 % yield increase on spring wheat (Menkovskaya Experiment Station of Agrophysical Institute — API) compared to conventional technology. Under the conditions of the North-West of Russia, the yield reached 60 kg/ha [10]. This was one of the first steps in mastering precise techniques of differentiated mineral fertilizer application. Fractional application of nitrogen fertilizers (with dose and treatment timing optimization) should be the next step. It is necessary to optimize the regimes of the use of fertilizers and ameliorants that are effective for several years in several crops in the rotation. To solve the above problems, reliable information on the status of crop and soil is required which will be provided by the accelerated development of mobile ground-based measuring instruments and more extensive use of optical and radar equipment for remote sensing [11]. The use of precision technologies such as delicate controls of the state of crops, biological preparations and hormones, required greater differentiation in the treatment with liquid and loose agrochemicals. Design and construction of such machines have been designed and patented in API [12]. In general, all of the above areas of high-precision technology development can become the basis for increasing yields by 20-25 % and more and fully developing the productive potential of varieties created using contemporary breeding and genetic methods.

Speaking of precision technology, we should not lose sight of the underlying innovative agricultural practices. Thus, K.G. Alimov, discovering the most sensitive phases of development during the growing season of crops and influencing plants by technological means, has achieved the roots going deep and consuming moisture from a depth of 1 meter. He used the well-known works of plant physiologists to stimulate root growth [13] which showed that with the water deficit in the soil, roots begin to move to the deep moist horizons. Deepening is stimulated by abscisic acid (ABA) the synthesis of which starts in plants during drought, inhibiting the growth of the aerial part but contributing to the development of the roots. If the crop is additionally treated with the ABA hormone in the appropriate phase (prior to the formation of the «number of grains per ear» trait) the root deeping is more intense. Nutrition optimization (manipulation by fractional application of nitrogen, effect of growth regulator and fungicide in the phases of ontogeny) results in the formation of 90-98 grains per ear instead of the usual 15-20 grains in the spring-summer drought in Siberia. At this, productive tillering remains not great (no more than two ears), which makes it possible to harvest crops before the snow. The unfertile stem ears are known to ripen 1 week later, and if the agronomist is waiting for their ripening (and they provide up to $^2/_3$ of the harvest), the field may go under the snow. This original technique is limited to the precise monitoring of developmental phases and adherence to the timing of the operations by the stages of organogenesis in accordance with them, i.e. it does not require any additional cost. Unfortunately, the assessment of the crop status is performed by eye, it is necessary to improve and gradually turn it into a fine instrumental estimation. In 1990, in the work-study unit NGAU Tulinskoe (Novosibirsk Region), K.G. Aliyev's technique provided 62-76 cwt/ha in the spring wheat and 62-63 cwt/ha in the spring varieties Kantegirskaya 89 and Lutescens 70 that emerged from the cooperative Siberian DIAC (diallel crossing) program. About 70-74 cwt/ha of the spring wheat have been produced for 4 years at the Ekaterininskaya station of the Institute of Plant Genetic Resources (VIR) (Tambov Region). In the field seasons of the 2000s, the spring wheat variety Esther provided yields of up to 75 cwt/ha in Ul’yanovsk Region. Under extreme drought, this technique provided yields of 30-35 cwt/ha in 70 % of experiments, while in the adjacent fields, where the conventional technique was applied, 10-12 cwt/ha only were produced.

These facts illustrate the improvement of drought resistance (due to artificial deeping of active roots into the moist soil horizon) resulting from technological methods. Of course, the depth and shape of the root system can be improved by genetic and breeding methods. Thus, in the drought-resistant Kazakhstanskaya 10 spring wheat variety of V.V. Novokhatin, R.A. Urazaliev, the originators (V.R. Villiams Kazakh Institute of Agriculture, Kaskelen, Almaty Region, Kazakhstan), the root system penetrated to a depth of 2.42 m in bogharic lands. Currently, intensive work is underway on the breeding management of the depth and shape of root systems starting with the phase of seedlings [14].

As mentioned above, fractional fertilization is of great importance. The same small fertilizer ($N_{30}P_{45}K_{45}$) dose was applied under spring wheat in two ways in the experiment performed by V.V. Kuznetsov and G.A. Dmitrieva [13]. These were the application completely or partially in the soil at plowing ($N_{15}P_{30}K_{30}$) and partly in the rows at sowing ($N_{15}P_{15}K_{15}$). In the second variant, as early as in the tillering stage, the total and active absorbing root surface increased by 1.5 times, and the grain yield increased by 1.5 times finally [13, p. 424].

There are real opportunities to improve the efficiency of attraction not by breeding methods only, though, as noted by V.V. Kuznetsov and G.A. Dmitriev, their effectiveness is high enough to made it possible to increase the percentage of grain to the total dry matter weight from 24 to 47% in corn and from 43 to 57 % in rice due to reached redistribution of assimilates (attraction gain) [13, p. 334]. According to them, under the technological impact on attraction intensity with hormonal treatment, the influx of sugar to the flowers increased 5 times, the influx of nitrogenous substances increased more than 2 times in 5 days after spraying tomatoes with 2,4-dichlorophenoxyacetic acid (2,4-D) [13, p. 331]. The authors note that assimilates move in the direction of higher hormone content since it is the hormones that create the attracting zones, regulate ATP synthesis and the H^+ pomp [13, p. 331]. The research on ear treatment with kinetin prior to the grain filling phase is very promising to enhance the attraction. At attraction, a competition for plastic material arises between the stem and the leaves. Healthy leaves prevent the outflow of assimilates to the ear. V.F. Altergot (Novosibirsk) proposed to treat the fields from aircrafts in the phase of the beginning of grain filling with senicats, the cheap minerals accelerating leaf aging. At senication, weakened leaves gave earnings the stock of plastic substances easier, and the yield increased by 4-5 cwt/ha. This aviatechnological method was widely used in the fields in Siberia in 1960-1970s, until the varieties with genetically enhanced ear attraction (including the ones resulting from the DIAC program) have been created.

Prospects for the development of breeding agrotechnologies and their possible contribution to improving yields. As noted by S. Borojevic, harvests once considered a record, became average in 20 years. It is known that as a result of breeding, the yield of soft winter wheat varieties has increased in Kuban by 44.9 cwt/ha, or 218.8 % since 1930 [15]. According to L.A. Bespalova, the yield of the winter wheat varieties created in the P.P. Lukyanenko Krasnodar Research Institute of Agriculture (Krasnodar NIISKh) sometimes reached 130 cwt/ha in 2013 (against the basic technology background). According to the information from the Head of the Tyumen Selection Center V.V. Novokhatin (personal communication, 2014), the yield of the recently created spring wheat variety Icarus averaged 45 cwt/ha and up to 75 cwt/ha with fertilized fallow (with basic technology) within the last 6 years in the area of several thousand hectares; the yield of the Tyumen zernokormovoy variety of triticale produced by V.V. Novokhatin is currently up to 120 cwt/ha in Tyumen Region.

There was a unique Przewalski variety test plot in the USSR Gossortoset system (at the eastern end of the Issyk-Kul lake in Kyrgyzstan). There, the yield was always 80-90 cwt/ha in all spring wheat varieties from Western Siberia with watering indicating quite normal systems of photosynthesis, respiration, energy transfer, and all ontogeny processes. In Siberia, the same varieties yielded 11-18 cwt/ha which clearly indicates their poor resistance to typical Siberian spring and summer drought which reduces the number of grains per ear and reduces the weight of 1000 grains against under the autumn cold. Today, various types of drought are the main lim-factors that limit the crop yield in the Russian Federation [16].

Genetic and breeding efforts to improve the drought tolerance of cereals have not resulted in serious findings for many years because the drought tolerance is a very complex multi-property feature formed by more than 20 traits; each of the traits is defined by tens and even hundreds of genes. It is almost impossible to find the «big» Mendelian gene which dramatically increases drought tolerance. To genetically enhance drought tolerance, other approaches based on the ecological genetics of quantitative traits are required. Most modern conventional and molecular geneticists tend to operate within a genetically centered paradigm, that is, continue to search for specific genes of drought tolerance, which is hardly promising. At the same time, there are more adequate systemic approaches to improve drought tolerance [17]. Poor genetic drought tolerance of modern cereal varieties results in annual losses to the economy of the Russian

Federation in the amount of 5.7 billion rubles.

Analysis of unique achievements in breeding. Let us consider the mechanisms for obtaining unique breeding results from the standpoint of the seven above-mentioned genetic and physiological systems.

Thus, V.S. Pustovoit increased the yield of sunflower oil from 20 to 55 %, which was not only an outstanding domestic but also a global achievement in breeding. The mechanisms of this revolutionary success have been carefully studied by A.B. D'yakov and V.A. Dragavtsev [18]. At the first stages of his research, V.S. Pustovoit estimated the percentage of oil per the achene core weight unit in various varieties using a special device purchased in the United States. He failed to find a significant breeding genetic diversity for these traits and even questioned the possibility of increasing the yield of oil through breeding. Then, it has not been known yet that (as in cultivars) oil content per the achene core cell is the same in wild forms (if the amount of oil per cell is increased, the cell just dies). However, he did not notice an interesting fact of a much greater yield of oil with 1 kg of seeds in thin-peeling varieties compared to thick-peeling ones («crunchable»). V.S. Pustovoшt understood that with the selection for the seed peeling thickness reduction (this meant lignification of a small number of outer layers only), the inner peeling layers that remain alive, increase the number of cells in the achenes core and consequently increase the yield of oil per flower baskets (or per plantation area unit). The peeling thickness can be felt by tongue, so the need for expensive American equipment disappeared. Thus, a unique breeding result was obtained by V.S. Pustovoшt mainly due to the MIC system. His associates used the IMM system as well, and managed to significantly enhance the immunity of varieties-populations. At the same time, the ATTR, AD, EFF, TOL, and ONT systems were not improving genetically (since no one worked on them) indicating substantial prospects for further breeding improving of sunflower.

The American Nobel Peace Prize winner Norman Ernest Borlaug, who worked in Mexico, made the first «green revolution» in the world (mainly with wheat) creating stunted (short-stem) varieties that did not lodge with high doses of nitrogen and abundant moisture (brought by irrigation and sub-tropical and tropical rains). He used only the «big» Mendelian genes of the short stem (and sometimes of dwarfism) but he never worked with the ATTR, MIC, AD, IMM, EFF, TOL, and ONT systems. Consequently, there are significant prospects for the second «green revolution», not only for wheat, but also for other genera and species of agricultural plants.

A famous scientist and breeder P.P. Luk'yanenko started his research at the Krasnodar Research Institute of Agriculture carefully studying the «bottlenecks» of the production process in the Kuban wheat winter varieties. According to L.A. Bespalova [19], P.P. Luk'yanenko conducted a thorough analysis of the factors that limit the yield of wheat in the Kuban. He was the first to realize that the reasons for low yields of winter wheat were brown rust, lodging, lack of early ripeness, and low ear productivity (add poor winter hardiness). The lack of early ripeness due to grain filling accounted for the unfavorable July heat was changed by genetical shifting the phase of filling to June. Selection for winter hardiness was carried out in special concrete containers (troughs) placed above the surface of the soil to ensure stronger root freezing in the mild winters compared to the soil. Mendelian genes of rust resistance were introduced in the varieties. In this way the Bezostaya 1 variety, a masterpiece of world wheat breeding, was created. Its yields immediately exceeded all the Kuban winter varieties by 10-15 cwt/ha. Obviously, P.P. Luk'yanenko perfected the AD, IMM and ONT systems, but the ATTR, MIC, EFF, and TOL systems were not improved in the creating the Bezostaya 1 variety.

The following radical increase in the yield of winter wheat in Kuban took place in 1980-1990-ies when Yu.M. Puchkov and L.A. Bespalova began to increase tolerance to thickening (TOL) by breeding methods. While the Bezostaya 1 variety is capable of supporting about 200 ears per 1 m^2, this value is 600 and 800 ears in the Spartanka and Skifyanka varieties, and 1,000 ears in the Kroshka variety created by L.A. Bespalova, with the yield gain reached 10 cwt/ha compared to the Spartanka variety. Thus, genetic improvement of only one of the seven systems (MIC in sunflower, TOL in winter wheat) may result in a drastic increase in yields.

The improvement of breeding and agricultural technologies. The models that make it possible to quantitatively describe strictly the contributions of all seven systems to increase yields were created in API [20-22]. The algorithms for the identification of genotypes and phenotypes and optimal selection of the parental pairs important for successful breeding were proposed based on these models. The next step is creation of special computer programs for automatic incremental implementation of the algorithms to optimally select the pairs for crossing, predict transgressions (and heterosis effects) and the algorithms for accurate identification of genotypes (by the productivity and yield components).

By 2013, in the API the development was completed of the priority theory of ecological and genetic organization of quantitative traits (TEGOQT) based on the discovery (1984) of a new epigenetic phenomenon. It was a change of the spectrum and the number of genes that determine any component trait of productivity under the changing environmental factor (lim-factor) that retards the growth of plants. 24 selection important consequences and nine breeding know-how were derived from this theory and experimentally studied [23-25].

Back in 1984, the first time in the world science, based on the great experimental material of the DIAC program, rigorous calculations of the possible breeding increase of the spring wheat yield in the territory from the Urals (Krasnoufimsk) to Transbaikalia (Ivolginsk) (along the parallel), and from Tyumen to Ust-Kamenogorsk (along the meridian) were made [26]. According to mathematical calculations, the limits of the genetic potential of yield increase (GPYI) variation versus the best variety in the sample of 15 varieties and 225 hybrids were 21-60 % (average of 41 %) between eight geographical points. Quantitatively, GPYI averages 8.5 cwt/ha with the average yield of the whole area of research of 21 cwt/ha. This potential can be rapidly realized in a breeding phytotron only with simulating the typical dynamics of various lim-factors for any region selecting parents for priority API algorithms and using ultra-precise methods of genotype identification by phenotype.

However, the above examples (i.e., search and evaluation of the years typical in the dynamics of the main lim-factors in a given geographical point for breeding and precise genotype identification by the maximum «genotype—environment» interaction effect by the component and resulting productivity traits against the background of the typical lim-factor dynamics) are only two possible approaches to ecological and genetic improving of productivity. The third area involves elimination of the effect of environmental lim-factors due to the stress AD systems involved in the critical phases of ontogenesis. This lever is capable of raising the yield by 30-40 %. Finally, the fourth possibility is to overcome the effect of limits in the daily dynamics of physiological processes of growth and development. The extension of their active state for 2 hours per day alone will provide an increase in the vegetative biomass equal to that of a late (9 days later) variety within 100 days of vegetation, and that is about 20-30 %. It is known that while one corn hybrid ripens just 10 days later than the other, the productivity of dry biomass may increase 2 times over this period compared to that accumulated by this hybrid plants by the time of the earlier one's ripening. The total potential ecological and genetic improvement of crop yields for spring wheat by four innovative breeding techniques in the extreme zone of Western Siberia is 50-70 %, and in the European part of Russia it is 70-90 %. Again, the implementation of these objectives should be based on new breeding techniques, with the most important element of the breeding phytotron.

Currently, the work is under intensive development to improve the agricultural and breeding technologies in the following areas: agrophysics, ecological genetics of quantitative productivity traits, plant physiology and biochemistry, phenotyping, ontogeny genetics, plant genetic resources, etc. [27-35].

Thus, we have found seven genetic and physiological systems (GPS) earlier, namely attractions, micro distribution of attracted plastic substances, adaptability, horizontal immunity, «payment» by plant dry biomass for the limiting factor unit in soil nutrition, tolerance to thickening, and genetic variability for the duration of ontogeny phases. Breeders and agricultural engineers have never really worked to improve each system separately, although this approach can provide the maximum increase of productivity. Some of these systems have been shown to be possibly improved through both agro- and breeding techniques, while the other part can be improved through the breeding methods only. Analysis revealed those GPS that have been perfected by the great breeders who have obtained outstanding results, and made it possible to understand what GPS have not been genetically improved, and therefore, retain the potential to increase yields in the future. The impact of hormones on the different phases of ontogenesis may be considered a promising area to manage the deepening of root systems, increase attraction and increase plant tolerance to stressors. It is important to note that the considered breeding and agro-technical reserves of the cereal yield increase should naturally complement each other, but not to be opposed to in any case: To implement a high crop genetic potential achieved by breeding methods, enhanced precision agricultural techniques are required, and vice versa, the most advanced technological methods may not give the desired result due to limited genetic potential of varieties. To combine agrotechnological and breeding reserves in solving the problems of agricultural sector, the creation of appropriate agrophysical instruments and equipment, construction of breeding phytotrons, development of information technologies, means of mathematical modeling and control of the processes of productivity and yield formation are required.

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