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Global Food Security and Fundamental Role of Fertilizer

Part 2. Fundamental Role of Fertilizer in Food Production[1]

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Vladimir N. Bashkin*,
Andrey O. Alekseev,
Institute of Physico-Chemical and Biological Problems of Soil Science of the Russian Academy of Sciences, Institutskaya str., 2, Pushchino, Moscow region, 142290, Russia

Abstract
The article shows the fundamental role of mineral fertilizers in solving the problems of global food security. Due to a number of reasons, primarily the increase in the cost of fertilizers and restrictions on their supply, as well as sanctions restrictions on the supply of raw materials, techniques for more efficient use of fertilizers are given. The role of precision agriculture is characterized, including issues of increasing the efficiency of fertilizer use. The results of agrochemical experiments with various crops and in various soil and environmental conditions are presented, their agronomic and economic efficiency is shown. Further directions of work on the evaluation of the effectiveness of the use of fertilizers, in particular nitrogen, are given. The risk assessment and management measures are also noted.

Keywords: mineral fertilizers; food security; precision agriculture; fertilizer use efficiency; mathematical models.

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Глобальная продовольственная безопасность и основополагающая роль удобрений

Часть 2. Основополагающая роль удобрений в производстве продовольствия[2]

Башкин В.Н.*,
Алексеев А.О.,
Институт физико-химических и биологических проблем почвоведения РАН,
142290, Россия, Московская обл., г. Пущино,
ул. Институтская, д. 2

Аннотация

В статье показана фундаментальная роль минеральных удобрений в решении проблем глобальной продовольственной безопасности. В силу ряда причин, прежде всего роста стоимости удобрений и ограничений на их поставку, а также санкционных ограничений на поставки сырья, приводятся методики более эффективного использования удобрений. Характерна роль точного земледелия, в том числе вопросы повышения эффективности использования удобрений. Представлены результаты агрохимических экспериментов с различными культурами и в различных почвенных и экологических условиях, показана их агрономическая и экономическая эффективность. Даны дальнейшие направления работы по оценке эффективности использования удобрений, в частности азота. Отмечаются также меры по оценке рисков и управлению ими.

Ключевые слова: минеральные удобрения; продовольственная безопасность; точное сельское хозяйство; эффективность использования удобрений; математические модели.

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Introduction

The increasing global production and use of mineral fertilizers is caused by the food consumption of the increasing population of the Earth and is predetermined by the shortage of basic nutrients, nitrogen, phosphorus and potassium, in various ecosystems, and above all, in agroecosystems and agricultural soils.

At the same time, it is known that, first of all, nitrogen is the most important component of protein and protein food in general, its biophility is extremely high, the biophility factor, i.e. the ratio of the content of this element in vegetation, and biota in general, in relation to the content in the lithosphere, is 160, in this sense nitrogen is second only to carbon (780), surpassing hydrogen (70) and oxygen (1.5) [1]. Nitrogen (N) is an essential element of proteins and other important biomolecules, and the availability of nitrogen in soil is a key factor limiting both natural and agricultural productivity in terrestrial ecosystems [2—6].

At the same time, it is known that the development of agriculture in recent centuries has largely been based on agrochemistry, which provides a scientific basis for the use of various fertilizers.

The development in the early twentieth century of a technology for binding atmospheric nitrogen (N_2) to ammonia (NH_3), known as the Haber-Bosch process, led to the emergence of the nitrogen fertilizer industry. These mineral fertilizers, including nitrogen, phosphorus and potassium ones, along with improved crop genetics and agronomy, contributed to the "Green Revolution", which led to a multiple increase in crop yields in many parts of the world, preventing hunger for a large number of people [7—9].

Currently, almost 270 million tons of mineral fertilizers are used annually in world agriculture, of which 169 are nitrogen, 51 are phosphorous and 53 million tons are potash [10]. However, due to a number of reasons, primarily the increase in the cost of fertilizers and restrictions on their supply, as well as sanctions restrictions on the supply of raw materials, it is necessary to address issues of more efficient use of fertilizers, since it is obvious that it will be difficult to expect an increase in their production in the foreseeable future.

Fertilizer best management practices aim to increase nutrient use efficiency and thus reduce adverse environmental impacts. In the case of phosphorus, the examples of sustainable phosphorus management — fractional application and use of efficient phosphorus fertilizers that do not contain high enough concentrations of cadmium and other toxic elements to pose a long term risk to the environment and possibly to human health.

The purpose of the 2d part of review is related to the issues of increasing the efficiency of the use of various types of mineral fertilizers in details, since it is obvious that the growth of their production and supply to various markets will slow down and even stagnate. Among the efficiency factors, both agronomic, agrochemical and biological, as well as social, will be characterized. The role of agricultural systems with the use of precision farming will be evaluated.

1. Precision farming

1.1. Precision farming and fertilizer efficiency

Precision farming is an approach to farm management that aims to identify methods that optimize the use of resources [11]. As a result, precision control is based on technologies that provide intensive collection, processing and evaluation of data necessary for the correct characterization and synthesis of temporal and spatial variability.

At the same time, it should be emphasized the special relevance of access to precision farming technologies in all agricultural regions of the world, including for small farmers in developing countries. FAO often raises this issue in its reports and makes great efforts to implement such approaches [12].

Theoretically, the difference in yield and environmental results is explained by measurable climatic, edaphic and managerial factors. Precision farming does not focus solely on the management of nutrients coming from fertilizers or from the soil, but improving the efficiency of their use is a common goal. Management of a specific site can help to adapt the introduced nutrients, improve the efficiency of their use, increase profits and/or minimize the risks of losses. First of all, this applies to nitrogen. For this element, it is necessary to diagnose the nitrogen regime of soils using various indicators, ranging from assessing the nitrogen mineralizing ability of soils [2] and ending with leaf diagnostics — see, for example, the work of V.V. Tserling [13].

At the same time, the calculation of Nitrogen Use Efficiency (NUE) at the field or contour level requires spatial tools to estimate the N content in cultivated plants. For example, the values of the nitrogen index can be used to determine whether the concentration of N in plants will be sub-optimal in comparison with the critical dilution curve to achieve maximum yield [14], while the sufficiency N index can be estimated by comparison with a well-fertilized field area [15]. The rapid estimation of NUE for a field or contour depends on remote sensing tools and algorithms that reliably monitor N concentrations in culture [16—19]. The working hypothesis is that the status of nitrogen sufficiency in culture is functionally related to the nitrogen content in the plant, expressed as concentration (%) or accumulation (kg N/ha) in the leaf or plant.

Although the indicators of chlorophyll or protein do not always coincide in terms of growth stages and the rate of fertilization, they can be used as a proxy test for assessing the status of N due to the strong relationship between N-containing compounds and N content [20]. Many different vegetation indices are widely used to assess the content and accumulation of N, accompanying factors (soil properties, humidity), which, as a rule, are calculated based on the reflectivity of leaves or the crown as a whole in the visible and near infrared range [21]. The rapid development of sensor technologies combined with machine learning (and other methods) has led to an increase in the ability to accurately predict yields and non-destructively assess the nitrogen status of plants. However, problems remain for practitioners, including the influence of the growth stage, varieties and the ability to manage these indicators in space and time, as well as the indices near the saturation levels. In addition, crown sensing data is often instantaneous, infrequent, and does not reflect the nitrogen status of the entire plant (i.e. vertical distribution), which potentially reduces the knowledge of the dynamic behavior of N in the plant necessary to make timely recommendations. To overcome these limitations, it is recommended to integrate hyperspectral data with crop growth models and radiation transfer models to improve estimates [20].

Differences in plant and soil data can also be used to determine the control zone of field contours using a combination of sensing, geostatistics and interpolation methods [22]. However, when developing specific plots, recommendations for precision farming should also take into account the dynamic nature of soil nitrogen and the efficiency of its absorption by agricultural crops in different landscapes. In addition, recommendations based on indicators during the growing season cannot serve as a guide for making decisions before sowing (planting).

In addition, an integrative site-specific approach to nitrogen management links geo-referenced models to support decision-making with dynamic biogeochemical models that model results based on relevant crop, soil, weather, management and enterprise factors [15, 16]. Models simulating N state can then be tested using field measurements collected during the growing season.

Thus, precision farming technologies are compatible within the adaptive control N system, in which specific empirical data on specific areas of the field level or contour are used to improve the accuracy of the model. Ultimately, data from these various sources can be combined using machine learning or other methods to provide the necessary assessments and automated recommendations [22].

Similar approaches can be used for other nutrients, both macro-elements (phosphorus, potassium) and meso- and micro-elements.

Crop sensing data and geo-referenced management data can be used to calculate and display the values of fertilizer use efficiency in space and time.

1.2. Efficiency of the use of various types of mineral fertilizers

Although currently the use of all mineral fertilizers has dramatically increased the biogeochemical flows of nitrogen, phosphorus and potassium, but nitrogen has been most affected.

The massive use of industrial nitrogen fertilizers has doubled the N fluxes in its global biogeochemical cycle, transforming it into an agrogeochemical one, with many environmental consequences [2]. Currently, it is necessary to reduce nitrogen losses during the cultivation of agricultural crops, while ensuring its sufficient resources to ensure food security. Modern achievements and problems related to the efficiency of nitrogen use in agriculture and the identification of research opportunities in the field of agrogeochemistry of nitrogen, its soil cycle and agronomy can be useful for achieving sustainable use of N in agriculture. As an environmental indicator, NUE assessments can help farmers assess the risk of N losses on farms or fields. It can also be useful for regional or supply chain assessments [23—26]. The technology of fractional fertilization can significantly reduce nitrogen losses with low plant demand on field circuits with a low level of fertility with a corresponding decrease in the rate of fertilization, in particular, for growing perennial grasses on these sites for reclamation or bioenergy. Thanks to modern technologies, the best way to capture unused N after the vegetation of the main crop is to use cover crops grown for rapid growth after the maturation of the main crop. This will help to remove unused nitrogen from the soil solution and reduce its losses in the environment. In the future, the absorbed nitrogen can be remobilized from the biomass of cover crops to ensure the main harvest of the next year.

These agrochemical and agronomic techniques can also be effectively used for better assimilation of both macronutrients (phosphorus, potassium) and meso-elements (sulfur, calcium), and trace elements necessary for plants.

1.3. Integration of knowledge with crop cultivation models

Next-generation computing platforms can study complex N, P, K interactions in crop systems to inform management, prioritize research, and improve understanding of complexities. These computational structures include statistical models, process-based mechanistic modeling models and their hybrids [27, 28].

So for nitrogen, such decision support tools explore all aspects of N in the soil-culture interface — from gene expression, crop physiology and phenology to soil processes and behavior prediction. Within the framework of such modeling (for example, APSIM, DSSAT models, etc.), the critical nitrogen concentration for crop growth is considered in the context of genetic, environmental and management factors (G × E × M) that control the interaction between nitrogen availability in soil, crop phenology, nitrogen distribution and yield [29], including biological nitrogen fixation (BNF) [30]. Models of farming systems are integrated assemblies of models of individual components that take into account specific biophysical components (for example, water balance, crop growth and mineralization of soil organic matter). They can be used to develop hypotheses, test them, and create management-oriented decision support tools that improve productivity, profitability, and environmental quality. Although statistical models are relatively easy to use and well suited for decision support tools, unlike process-based models, they cannot be extrapolated beyond the context (G × E × M) in which they were developed. Consequently, they cannot predict the change in the values of the efficiency of fertilizer use depending on the un-programmed combinations (G × E × M). However, their potential can be significant for two reasons. Firstly, experiments alone are not enough to solve many potential combinations (G × E × M) resulting from the interaction of farmers' solutions and the weather. In a given field and in a given year, the results of farming systems are the result of billions of potential combinations of hundreds of variables. Some of them are chosen by the farmer (for example, the variety, planting date, use of soil and fertilizers), while others depend on weather conditions and climate. Secondly, in theory, new strategies for managing fertilizer and crop systems can be considered to increase the effectiveness of field experiments and determine research priorities based on sensitivity analysis, which identifies scenarios with serious consequences. At the same time, field experiments will help to identify and fill gaps in the knowledge of models.

1.4. Significant areas of research to increase the efficiency of fertilizer use

Historically, the values of the efficiency of fertilizer use, in particular for nitrogen, in agricultural systems have been transformed from high values in systems with low costs and low productivity through low values in systems with high costs and high productivity to moderate values in systems with moderate costs and high productivity [31].

In fact, some existing systems with low costs and low productivity, for example, in Benin or even India, demonstrate Nitrogen Use Efficiency (NUE) > 1, which means net use of soil nitrogen and a decrease in soil fertility. Although in many countries there is a sharp decline in NUE values in agriculture with the introduction and excessive use of N fertilizers (for example, NUE in China fell below 0.3), it is believed that this is not inevitable and that countries experiencing a downward trend in the values under consideration could learn from those who were able to "bend" their curves of changes in NUE values towards higher indicators (> 0.6 in the USA and France) due to public policy, education, careful management, etc. [31, 32].

As the historical trajectory shows, simply increasing the efficiency of fertilizer use alone will not be enough if it leads to low-production systems and food insecurity among the growing world population. Thus, we are faced with a complex, multi-purpose problem, which is further complicated by dynamic economic and environmental factors. Profitability may be relatively insensitive, in particular, to doses of N fertilizers. For example, in the Midwestern United States, when growing corn, expenditure budgets showing the return on investment in nitrogen fertilizers (for example, the ratio of the cost of nitrogen fertilizers and the profitability of grain) show that the economically optimal doses of nitrogen N fluctuates by as much as 50 kg N/ha, based only on the real differences in the ratio "nitrogen fertilizers: grain prices" (for example, 0.05—0.20) [33]. 50 kg N/ha is ≈30% of the average economic optimal dose of N for these systems. Consequently, if there are economic incentives to optimize nitrogen application doses, they strongly depend on grain and fertilizer markets.

Taken together, these problems require a reliable interdisciplinary approach to improving NUE using multi-purpose optimization that takes into account social and biophysical sciences. Multi-purpose optimization is a computational framework that looks for optimal solutions and takes into account trade-offs between potentially conflicting goals, such as minimizing data on the supply of nutrients while maximizing data on yield output. Such compromises are captured by the modeling of agricultural systems, which are powerful integrators for the use of multi-purpose optimization methods. While modeling can only be used to maximize the fertilizer utilization rate, it is instead possible to maximize profitability and cost-effectiveness while minimizing nutrient losses at the same time. Multi-purpose methods have been used to optimize the simulation parameters of the corn growing system in accordance with empirical results [34], but can also be applied to optimize goals aimed at NUE indicators. On a regional scale, these optimization methods were used to distribute rain-fed and irrigated areas in order to maximize yields and minimize environmental impacts [35], therefore, similar concepts could be used to maximize the values of the efficiency of the use of nutrients in different regions or around the world. For example, compromises in goals have also been identified in crop breeding, in particular, between the total grain yield and the concentration of N in the grain, but recent work with genomic selection on several grounds opens up significant prospects [36]. Therefore, it can be suggested that a clear consideration of the set of goals within the optimization framework will be crucial for future progress in increasing the fertilizer use efficiency (FUE) while simultaneously achieving food security and optimizing economic indicators [37].

2. Case studies

In this section, it is necessary to consider examples of the rational use of fertilizers in various agricultural regions. This allows us to emphasize once again the fundamental role of mineral fertilizers in obtaining sustainable and economically justified yields of various crops. This has been evaluated in numerous recent publications [39—51].

2.1. Vegetable crops

Cabbage

Russia

The development of vegetable growing in any country is aimed at fully meeting the needs of the population in vegetables and is based on the use of a certain level of production of intensive crops. Carrots during the growing season require a continuous supply of nutrients. At the beginning of growth, it is particularly demanding for nutrients in a highly soluble form. At this time, the plant consumes the most nitrogen. During the growth period of root crops, the need for phosphorus and especially for potassium increases. In two-year studies (2019—2020) on sod-podzolic soil in the Moscow region, Russia, authors studied the effect of foliar top dressing for vegetation with liquid complex fertilizer, LCD, with a ratio of N and P equal to 11:37, consists mainly of ammonium polyphosphates) on various mineral nutrition systems. The experimental plot soil has the following agrochemical indexes: humus matter — 1.54%, pH_{KCl} — 6.1 and 6.63, content of mobile forms of P_2O_5— 437 and 199 mg/kg of soil, K_2O — 220 and 211 mg/kg of soil, in 2019 and 2020, respectively. In the experiments, phenological observations were carried out, the characteristics of the development of vegetables under various food systems were evaluated, the day before harvesting, the biometric indicators of carrots were evaluated according to the experimental variants. Guided by generally accepted methods, additional income from the use of fertilizers was determined according to the control variants. The maximum increase in commercial yield in comparison with the control, on average for two years of research, was obtained in the variant N92P76K69(S5) with the use of four top dressing

(N11P37) and amounted to 8.7 t/ha. When reducing the total dose of nitrogen by 35 kg in the active substance to N57P90K120(S20)+28CaO, the yield increase to the control was 5.6 t/ha. On average, for two years, the largest amount of conditional net income was obtained in the variant N92P76K69(S5) with the use of four top dressing and amounted to 83 thousand rubles/ha, which exceeds the other variants by 35–36 thousand rubles/ha.

2.2. Root vegetables

Table beet

Russia

Table beet in the process of growth forms a large volume of biomass, which causes its increased need for nutrients. As a result, during the growing season this crop requires a continuous supply of nutrients. Nitrogen consumption continues throughout the growing season, but the maximum shortage can occur during the phases of formation of a powerful leaf apparatus, root growth, so it is advisable to split nitrogen fertilization during the growing season, using fertilizer urea. Both the lack of nitrogen and phosphorus reduces the attaining of high yields. With low application rates of complex fertilizers, phosphorus deficiency can be partially corrected by applying LCF. In two-year studies held on a sod-podzolic soil in the Moscow region, authors studied the effect of foliar fertilization with complex fertilizer under various mineral nutrition systems. In the experiments, phenological observations were carried out; the characteristics of crop development under various nutrition systems were evaluated. The day before harvesting, the biometric parameters of table beet were evaluated through the experimental treatments, and, based on generally accepted approaches, additional income from the use of fertilizers was determined when compared to the control treatment. The maximum increase in marketable root yield over control, on average for two years of research, was obtained in the treatment receiving N88P65K69(S5) with two N11P37 foliar applications and amounted to 8 t/ha. When reducing the total nitrogen rate by 16 kg/ha to N72P79K120(S20)+28CaO, the yield increase over control was 7.3 t/ha. On average for two years, the largest extra income was obtained in the N88P65K69(S5) treatment with two foliar applications that amounted to 86 thousand rouble/ha, exceeding the other treatments by 12—29 thousand ruble/ha.

2.3. Potatoes

Russia

The study of the effect of liquid and granular phosphorus-containing fertilizers on the yield and quality of potato tubers on gray forest soil was carried out in the Kaluga region, Russia. When setting up this experiment, one proceeded from the following postulates.

With 1 ton of potato tubers, an average of 3 kg N; 1.5 kg P_2O_5; 6.5 kg K_2O and 0.3 kg S are alienated from the soil. Under potatoes, it is required to add more potassium than nitrogen and phosphorus, since potatoes are a potassium-loving culture. Optimizing the nutrition of potato plants with phosphorus contributes to the better use of nitrogen by plants, increases the starch content in tubers, accelerates maturation and improves the keeping quality of tubers. Balanced mineral nutrition of potatoes reduces the damage of plants by fungal and viral diseases (Fig. 1).

Figure 1. The mass fraction of commercial potato tubers in the fertilized versions of the experiment was in a close range: 83.8—85.8%. In the control version of the experiment, the marketability of tubers was noticeably lower (71.6%)

Рис. 1. Массовая доля товарных клубней картофеля в удобренных вариантах эксперимента находилась в близком диапазоне: 83,8—85,8%. В контрольном варианте эксперимента рыночность клубней была заметно ниже (71,6%)

The conducted research allowed us to draw the following conclusions:

• When cultivating potatoes in 2020 on gray forest soil with very low availability of nitrate nitrogen, very high availability of mobile phosphorus and high availability of mobile potassium, the maximum increase in yield of commercial tubers relative to control without fertilizers, equal to 93%, was obtained by applying N97P75K90S6 (kg/ha) with a combination of the following brands of fertilizers:

– LCF+,NPK(S)+Ca 5:15:30(5)+7CaO for pre-planting cultivation;

– urea for pre-planting cultivation;

– LCF, NP 11:37 — foliar top dressing in budding.

• The most balanced mineral nutrition of potatoes is achieved by using complex nitrogen-phosphorus-potassium fertilizers with a high potassium content.

• The introduction of N97P75K90S6 when combining LCF, NPK(S) 8:20:30(2) and urea before planting with foliar top dressing LCF, NP 11:37 gave a high economic result — additional income relative to the control amounted to 170 thousand rubles/ha (excluding the cost of fertilizing, as well as harvesting the crop increase).

Furthermore, the effect of non-root treatment with Si-containing agrochemicals on the yield and quality indicators of potato tubers when growing for seed purposes is evaluated. The experiments were laid at the experimental base Korenevo of the Russian Potato Research Center in the Moscow region in 2019—2020. The effect of non-root treatments with silicon-containing agrochemicals in increasing doses on the productivity of seed potatoes of the Golubizna variety was studied. Spraying of plants with the preparation from 100 to 1000 g/ha in the physical weight of the agrochemical was carried out in the budding phase — the beginning of flowering at the consumption of the working solution of 300 l/ha. The scheme of the experiment included eight variants in a four-fold repetition. The standard power supply system is N90P90K135. The structure of the crop of potato tubers was determined by weighing the fractions from each plot, taking into account the transverse diameter: small fraction — less than 30 mm; seed fraction — from 30 to 60 mm; food-tubers more than 60 mm. Spraying potato plants with silicon-containing agrochemicals during the budding phase — the beginning of flowering increases the gross yield and marketability of seed tubers, as well as increases the yield of nutritionally valuable components. The maximum gross yield of tubers was obtained in variants with the introduction of 270—384 g of SiO_2/ha. The increase in the yield of tubers at the same time amounted to 4.9—8.5 t/ha. In turn, for the variants with a dose of 270—384 g of SiO_2/ha, the best starch yield indicators were achieved (8.6—8.7 t/ha) and vitamin C (7.9—8.3 t/ha).

2.4. Sugar beet

Poland

Optimization of the mineral nutrition of sugar beet with macro- and meso-elements during the spring application of the main fertilizer was performed on podzolic soil of light granulometric composition in Poland.

In this project, which was carried out for 3 years (2018, 2019 and 2020), the following strategy of feeding sugar beet on podzolic soil of light granulometric composition was applied:

• inclusion of both macro- (nitrogen, phosphorus, potassium) and meso-elements (sulfur, magnesium) in the plant nutrition program in balanced proportions, it allows you to achieve the best yield of root crops;

• optimization of plant nutrition with macro- and meso-elements increases the collection of sugar per hectare.

In favorable weather conditions for sugar beet in 2020, when cultivated on podzolic sandy loam soil with a neutral reaction of the soil environment, an average supply of nitrate nitrogen, a very high supply of mobile phosphorus, an average supply of mobile potassium and an average supply of exchangeable magnesium, the maximum yield of root crops (118.2 t/ha) was obtained using the following mineral nutrition scheme (with by adding in kg/ha N130P60K141S52Mg12):

• LCF, NPK(S) 15:15:15(10) before sowing;

• kalimag before sowing;

• ammonium nitrate for top dressing at the end of March.

The system of applying mineral fertilizers for sugar beet, which included the introduction of complex fertilizer LCF, NPK(S) 15:15:15(10) and kalimag before sowing, as well as fertilizing with ammonium nitrate, generated a high additional income equal to 708.1 euros/ha, excluding the cost of harvesting the crop increase.

2.5. Silage crops

Corn

Russia
In a number of agrochemical experiments, it has been shown that insufficient doses of fertilizers with low soil fertility lead to a strong risk of crop shortage of green corn mass. In this project, carried out for 2 years (2019 and 2020) on sod-podzolic sandy loam soil with high potassium availability, the following strategies for feeding silage corn were used:

- combination of macro-, meso- and microelements (nitrogen, phosphorus, sulfur and zinc) is a necessary condition for intensive biomass accumulation;
- if the soil is highly supplied with potassium, it is permissible to use brands of complex fertilizers that do not contain potassium, but it is necessary to take into account the prospect of depletion of soil fertility;
- foliar fertilizing with phosphorus is a justified technique that improves the phosphorus nutrition of plants, especially in conditions of cool spring.

Based on the conducted experiments, the following conclusions were made:

When cultivating silage corn in 2020 on sod-podzolic sandy loam soil with medium availability of mobile phosphorus and high availability of mobile potassium, the maximum yield of green mass (52.8 t/ha) and dry matter (15.8 t/ha) was achieved through the use of the following mineral nutrition scheme with nitrogen, phosphorus, sulfur and zinc (in kg/ha N163P90S56Zn1,6):

- LCF+, NP(S)+Zn 20:20(14)+0.4Zn for pre-sowing cultivation;
- Urea for pre-sowing cultivation;
- LCF, NP 11:37 — foliar top dressing at a plant height of 10—15 cm.

Lithuania
In the conditions of 2020, which was characterized by cold weather in May, with a fractional application of phosphorus (80 kg P_2O_5 / ha before sowing + 10 kg P_2O_5 / ha — foliar top dressing) obtained a high yield increase of green mass of corn and dry matter equal to 12%. The above-mentioned system of application of fertilizers for silage corn (N163P90S56Zn1,6) with the introduction of a small part of phosphorus in foliar fertilization allowed to obtain a high additional income of 341.0 euro/ha relative to the standard system of application of fertilizers in the region with the introduction of nitrogen-phosphorus fertilizers in lower doses (N140P60). The costs of harvesting the resulting crop increase were not taken into account.

Sunflower

Russia
Also in the Moscow region, Russia, an experiment was conducted on the use of liquid complex fertilizer and sulfur-containing complex granular fertilizer in the technology of sunflower cultivation on sod-podzolic soil. Based on the results obtained, it was shown that when sunflower was grown on sod-podzolic soil with a medium acidic reaction, low availability of mobile phosphorus and medium availability of mobile potassium, high seed yield (2.79 t/ha at standard humidity) was achieved when N76P30K30S20 (kg/ha) was introduced into the soil by using the following two fertilizers: urea for pre-sowing cultivation; NPK(S) 15:15:15(10) during sowing. The adjusted system of applying fertilizers for sunflower with the introduction of all the nutrients necessary for plants (nitrogen, phosphorus, potassium and sulfur) into the soil was 24% more expensive than the nutrition system without potassium and sulfur, but provided additional income in the amount of 1,200 rubles/ha, excluding the cost of fertilizing the soil, and also for harvesting and refining the crop increase.

2.6. Grain crops

Spring wheat

Russia
The study of the effectiveness of the use of urea with different methods and terms of its use in the fertilizing of spring wheat was carried out on a typical chernozem in the Tambov region, Russia. It is known that due to the balanced provision of plants with all the necessary nutrients, it is possible to maximize the realization of the genetic potential of productivity. It is important to use the correct form of fertilizers, as well as the timing and methods of application. In different phases of growth and development, wheat needs different amounts of nitrogen. The amide form of nitrogen, as is known, quickly penetrates through the leaf surface of plants and is included in the processes of nitrogen metabolism.

When developing the spring wheat nutrition program, the following approaches were taken: fractional application of nitrogen fertilizers with a combination of pre-sowing application and several non-root fertilizing can be an effective method of increasing grain yield and quality; identification of the optimal timing and methods of urea application for maximum realization of genetic potential with a single dose of application.

The conducted experience allowed us to draw the following conclusions:

- The maximum yield of spring wheat grain on typical chernozem was obtained by carrying out two non-root fertilizing with urea (N30 + N30) against the background of pre-sowing application of a mixed fertilizers to the soil, consisting of a grade of complex fertilizer PK(S) 0:20:20(5) and urea (P40K40S10 + N20).
- The increase in yield relative to the control version of the experiment, where fertilizers were not applied, was 250%. The double use of urea in the phases of the tube and the flag sheet gave a very high operating income of 11,243 rubles/ha. From an economic point of view, the transfer of 75% nitrogen to fertilizing on spring wheat is of interest when it is used once in the early phases of crop development (before earing). This technique provides the smallest number of technological operations for the introduction of urea solutions and gives an operating income relative to control without fertilizers of more than 4.5 thousand rubles/ha.
- Fractional application of nitrogen fertilizers (25% before sowing and 75% in top dressing) makes it possible to optimize nitrogen nutrition of plants with a high initial supply of the upper soil layer with mineral nitrogen, which is mainly in ammonium form.

Lithuania

The study of the effect of complex granular and liquid fertilizers on the yield and grain quality of spring wheat was carried out on the sod-podzolic sandy loam soil of Lithuania. In this project, carried out over 2 years (2019 and 2020) on soil with high potassium availability, the following strategies of spring wheat nutrition were used:

- optimization of plant nutrition with nitrogen and phosphorus is a necessary condition for obtaining high yields and high grain quality;
- if the soil is insufficiently supplied with mobile phosphorus, it is necessary to apply increased doses of phosphorus in the main application.

Conclusions from this experience:

When cultivating spring wheat in 2020 on sod-podzolic sandy loam soil with medium availability of mobile phosphorus and high availability of mobile potassium, the maximum grain yield (3.85 t/ha), as well as the best values of quality indicators (grain nature, sedimentation), were obtained when adding N100P90 as part of the following fertilizers:

- LCF, NP 11:37 sprayer for pre-sowing cultivation;
- ammonium nitrate for pre-sowing cultivation;
- ammonium nitrate in top dressing randomly at the BBCH 30 stage (the beginning of the exit into the tube).

The above-mentioned spring wheat mineral nutrition technology (N100P90) made it possible to achieve a good economic result compared to the standard regional technology (N100P60). The additional income amounted to 120.6 euros/ha, excluding the costs of harvesting and refining the resulting crop increase

Winter wheat

Russia

It is known that with 1 ton of winter wheat grain, an average of 19 kg of N, 8 kg of P_2O_5 and 4.8 kg of K_2O are alienated from the soil. Sufficient provision of plants with phosphorus improves the overall and productive bushiness, promotes overwintering, increases the efficiency of water use by plants, accelerates maturation and reduces grain moisture during harvesting. During the spring cold snap, winter crops often lack phosphorus due to a decrease in its intake into plants.

Liquid complex fertilizer (LCF) with a ratio of N and P equal to 11:37, consists mainly of ammonium polyphosphates. In soil, polyphosphate chains are broken down to monomeric phosphates (undergo hydrolysis) under the action of enzymes produced by soil microorganisms and plant roots, or without the action of enzymes. Approximately half of the polyphosphates are destroyed within 1—2 weeks. A small part of phosphorus in the composition of liquid complex fertilizers is represented by monomeric phosphates, which are immediately available to plant roots.

In this project, which was carried out for 5 years on leached chernozem, the following winter wheat nutrition strategy was used:

- the use of phosphorus in both solid and liquid complex fertilizers allows for a high increase in grain yield;
- reducing the nitrogen dose in dry years does not lead to a decrease in yield, but does not allow you to get high-quality grain.

When growing winter wheat on gray forest soil of the Orel region, Russia, the combination of urea top dressing with non-root top dressing LCF, NP 11:37 contributed to the formation of the most full-fledged grain with the maximum protein and gluten content. The increase in winter wheat grain yield from foliar fertilizing with LCF, NP 11:37 in the phase of tillering and the phase of milk ripeness was in the range of 0.28—0.32 t /ha at standard grain moisture or 4—5% compared to standard farming practice, which includes only nitrogen fertilization with ammonium nitrate. The additional income received due to carrying out two non-root fertilizing of winter wheat with liquid complex fertilizer of housing and communal services NP 11:37 is estimated at 2186—2204 rubles/ha, excluding the costs of harvesting and refining the crop increase.

In the arid conditions of 2020, when cultivating winter wheat on leached chernozem in the Krasnodar Territory, Russia, with increased availability of mobile forms of phosphorus and potassium, mineral nutrition with the addition of N49–93 and P92–162 in kg/ha provided an increase in grain yield by 81—103% relative to the control without fertilizers. Food grain of the 3rd class was grown in a variant of the experiment with the introduction of N93P81 by combining the following brands of fertilizers: LCF, NP 11:37 in autumn for disking (N24P81); ammonium nitrate — early spring fertilizing (N69). At the same time, grain yield did not significantly differ in the variants where diammonium phosphate NP 18:46 and LCF, NP 11:37 (5.27—5.47 t/ha) were used as phosphorus-containing fertilizers. At the same time, grain yield was significantly lower in the variant using ammophos NP 12:52 as a phosphorus-containing fertilizer compared to variants with using LCF, NP 11:37. The reduced nitrogen dose (48 kg N/ha) in the dry season was sufficient to obtain a good yield of 5.47 t/ha of grain. In the latter variant, LCF, NP 11:37 was used for the main application to the soil and for fertilizing. However, the phosphorus dose is too high (162 kg P_2O_5/ha) and it certainly should not be used with the development of erosion processes and the risk of phosphorus losses to surface reservoirs. The best economic result was also obtained when N24P81 + N69 was added to kg/ha by combining LCF, NP 11:37 and ammonium nitrate. Additional income relative to control amounted to about 35.8 thousand rub/ha without taking into account the costs of fertilizing and harvesting the crop increase.

In field experiments, conducted on soddy-podzolic heavy loam soils in the Moscow region, the effect of use of Si-containing agrochemical on yield and quality parameters of winter wheat grain was studied. Soil had a medium level of available phosphorus and potassium, as well as a low level of available sulfur, and therefore a balanced grade of sulfur-containing complex fertilizer NPK(S) 15:15:15(10) was applied as a basal fertilizer. Weather conditions in 2018—2019 and 2019—2020 growing seasons were characterized by an excessive precipitation. It is known that silicon optimizes the metabolic processes in plants, strengthens the stem that prevents lodging of cereals. The Si-containing agrochemical was used in increasing rates in winter wheat Moskovskaya 56 variety. During two experimental years the highest yield of winter wheat grain was obtained in the treatment with seed coating with Si-agrochemical at 50 g/t seeds and foliar sprays at 100 g/ha at the beginning of stem elongation and the beginning of heading. In the above-mentioned treatment, the use of Si-agrochemical increased grain yield by 19—26%. Si-containing agrochemical had a positive effect on spike length, 1000-grain weight and test weight of grain.

Poland

Study of the effectiveness of early spring winter wheat fertilizing with complex fertilizers on podzolic soil of light granulometric composition in Poland allowed us to conclude that under conditions of insufficient moisture in the 2019—2020 season, when cultivating winter wheat on soil with a neutral reaction, high availability of nitrate nitrogen, very high availability of mobile phosphorus and average availability of mobile potassium, the maximum grain yield (5.58 t/ha) was achieved with the use of the following system of application of mineral fertilizers (with the addition in kg/ha N150P85K145S30):

- double superphosphate before sowing;
- potassium chloride before sowing;
- NPK(S) 15:15:15(10) — top dressing in mid-February;
- ammonium nitrate — 2 top dressing (in mid-February and mid-March).

The winter wheat fertilizing scheme, which included the early spring application of ammonium nitrate and complex fertilizer NPK(S) 15:15:15(10) and the second fertilizing with ammonium nitrate in a month, generated additional income of 118.4 euros/ha, excluding the cost of harvesting and refining the crop increase.

Italy
The study of the effectiveness of early spring fertilizing at two experimental sites of the University of Milan in 2017—2018 with winter wheat was conducted.

Treatments A, B, C, D refer, respectively, to: (i) unfertilized (control), (ii) fertilized according to the farmer's experience (with local fertilizers), (iii) like B but with new fertilizers, (iv) like B but with S- and Zn-enriched fertilizers.

Fertilizers were:

- Treatment B: DAP (18-46-0) [origin of phosphate rocks was Tunisia in one site, Morocco in the other] + ammonium nitrate [provided by the farmer] + urea [provided by the farmer];
- Treatment C: DAP (18-46-0) + ammonium nitrate [provided by the farmer] + urea [provided by the farmer];
- Treatment D: NP+S+Zn (16-34-0)(6)(0.4) [Russia] + ammonium nitrate [provided by the farmer] + urea [provided by the farmer] (Table).

Cultivar Obelix (Syngenta) was sown on 11 October 2017 in the first (named "Bonatti" hereafter; latitude 45°00'47.8" N, longitude 9°57'10.7" E; https://goo.gl/maps/3nX4UxEmrsm) and second field ("Capannone" hereafter; latitude 45°01'24.6" N, longitude 9°57'42.5" E; https://goo.gl/maps/dZ1PrK5AGQC2

The positive effect of sulfur on the number of spikes per plant and of grains per spike was already observed for winter wheat by Järvan et al. [45]. This led to a slightly higher harvest index (grain biomass to total aboveground biomass ratio) for treatment D as compared to other treatments.

Sulfur did not affect stem elongation [46—49], as differences in plant height were mainly among unfertilized (treatment A) and fertilized (treatment B, C, and D) plots. This is a key point since higher plants are more susceptible to lodging, one of the main abiotic factor affecting wheat productivity and grain quality. No effect of treatments was found for grain size or grain weight, in agreement with what reported by different authors.

Concerning the Capannone site, results from the 2017/18 campaign are in line with those of the Bonatti one, with treatment D showing the highest yield and treatment A the lowest. Plants fertilized with addition of sulfur and zinc (treatment D) had the greatest number of spikes per plant and of grains per spike as observed in the other field Bonatti (Fig.2), although variability among field replicates prevented results to be statistically significant. Even in this case no effect of sulfur on plant height was found, confirming the absence of negative side-effects of sulfur fertilization (no increase in susceptibility to lodging). As observed in the Bonatti site, fertilization treatments did not affect neither grain size nor grain weight.

Such agreement between results obtained in the two sites is relevant, as it clearly shows that the effect of the previous crop in the Capannone field (tomato) — which hidden the effect of sulfur and zinc during the first-year campaign — is progressively fading.

The positive effect of sulfur on crop productivity was relevant and, in this second year campaign, also statistically significant. Moreover, sulfur application did not have any impact on plant height, and thus on potential increase in susceptibility to lodging.

Table. Scheme of fertilizer application

Таблица. Схема внесения удобрений

Total amounts of fertilizers distributed (kg/ha)					
Treatment	P_2O_5	N	K_2O	S	Zn
A	—	0	—	—	—
B, C	80	160	—	—	—
D	80	160	—	14.1	0.94

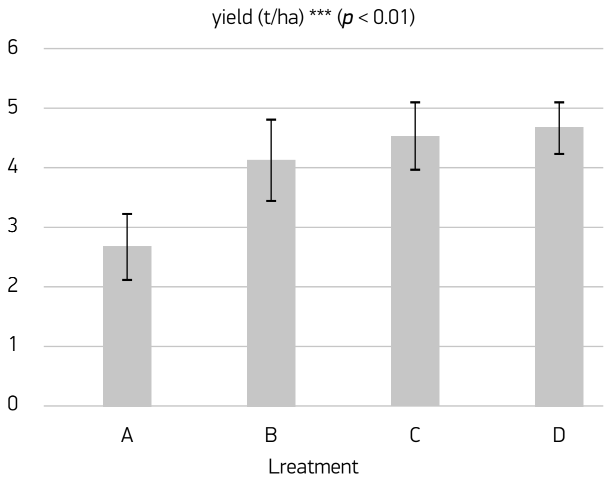

Figure 2. Yields in the Bonatti site, t/ha

Рис. 2. Урожайность на участке Бонатти, т/га

Romania

The study of the comparative effectiveness of liquid and granular phosphorus-containing fertilizers in the cultivation of winter wheat was carried out on chernozem soil in Romania. At the same time, liquid complex fertilizers based on ammonium polyphosphates are an effective form of phosphorus on soils that contain calcium carbonate.

The study showed that the minimum NDVI values were obtained in the control version of the experiment. The NDVI values in the fertilized variants of the experiment were statistically equivalent. Consequently, when cultivating winter wheat in the dry season of 2019—2020 on chernozem soil with low availability of phosphorus available to plants and medium availability of easily exchangeable potassium, the best grain yield of 4.03—4.07 t/ha was obtained by adding N175P60 and N184P74 to kg/ha using the following mineral fertilizers:

- LCF, NP 11:37 sprayer for pre-sowing cultivation;
- urea — top dressing randomly in the phases of tillering and the beginning of the exit into the tube.

The increase in gross revenue when introducing N175P60 as part of LCF, NP 11:37 and urea is estimated at 307 euros /ha relative to the control. Based on the costs of purchasing and applying fertilizers, this system of applying fertilizers was economically the most profitable.

Hungary

The study of the comparative effectiveness of liquid and granular phosphorus-containing fertilizers in the cultivation of winter wheat was carried out on meadow-chernozem soil in Hungary. In the field experiment conducted on meadow-chernozem soil, the following strategies of winter wheat nutrition were used:

- liquid complex fertilizers based on ammonium polyphosphates are the most effective form of phosphorus on soils containing calcium carbonate;
- to achieve maximum yield on soils with low availability of phosphorus available to plants, it is necessary to use increased doses of phosphorus-containing fertilizers.

At the same time, the following conclusions and conclusions were obtained:

When cultivating winter wheat in the dry season of 2019—2020 on meadow-chernozem soil with low availability of phosphorus available to plants and high with easy-exchange potassium, the maximum grain yield of 3.45 t/ha was obtained by applying a reduced dose of nitrogen and an increased dose of phosphorus (N123P104) by combining the following mineral fertilizers:

- LCF, NP 11:37 sprayer for pre-sowing cultivation;
- LCF, NP 11:37 — top dressing in the tillering phase;
- urea — two top dressings at random in the tillering phase and the beginning of the discharge into the tube.

The increase in gross revenue relative to control when using the above-mentioned fertilizer application system is estimated at 162.2 euros/ha. This is the only fertilizer application system with the generation of additional income relative to control, taking into account the costs of purchasing and applying fertilizers.

Brazil

The study of the comparative effectiveness of the application of complex and mixed fertilizers in the cultivation of wheat was carried out on degraded red latosol in Brazil. At the same time, it is known that wheat is an important agricultural crop in Brazil, and the south of the country is its granary for this culture.

When growing wheat in the 2019 season on degraded red latosol with a very high availability of phosphorus and potassium forms available to plants and a high availability of available sulfur, the use of complex fertilizers NP(S) 14:40(7) and NPK 12:32:16 during sowing provided an increase in grain yield by 5—7% relative to farming practice with by adding a mixture of the composition NPK 05:20:20 during sowing.

Wheat grain suitable for baking purposes was obtained using a nutrition scheme that included a sulfur-containing complex fertilizer (with the introduction of N120P80K80S14 (in kg/ha):

- NP(S) 14:40(7) in rows during sowing;
- potassium chloride scattered after sowing;
- urea — fertilizing randomly in the phases of tillering and the beginning of the discharge into the tube.

The above scheme of wheat nutrition with the use of sulfur-containing complex fertilizer NP(S) 14:40(7) during sowing, according to preliminary estimates, was the most cost-effective.

Corn

Serbia

The study of the comparative effectiveness of different grades of granular fertilizers was carried out on chernozem soil in Serbia. Based on this experience, the following conclusions were made.

In 2020, when growing corn on carbonate chernozem with low availability of mobile phosphorus and medium availability of mobile potassium, the maximum grain yield (11.03 t/ha) was obtained using macro-elements in doses of N100P80K60 by applying the following mineral fertilizers for pre-sowing cultivation:

- ammophos NP 12:52;
- urea;
- potassium chloride.

The increase in gross revenue when combined before sowing of ammophos NP 12:52, urea and potassium chloride (N100P80K60) is estimated at 486.7 euros/ha relative to the scheme of application of farm fertilizers with an overestimated dose of nitrogen and an insufficient dose of phosphorus (N156P64K64).

Brazil

The effectiveness of the application of sulphate sulfur as part of complex fertilizers on the yield of corn grain cultivated on degraded red latosol in Brazil was studied.

The conclusions obtained:

When growing corn in the dry winter season of 2020 on degraded red latosol with an average content of phosphorus and potassium forms available to plants and a satisfactory supply of available sulfur, a competent selection of sulfur-containing fertilizers is a combination of NP(S) 14:40(7) grade and elemental sulfur (50% sulphate sulfur + 50% elemental sulfur) or the same application is only NP(S) 20:20(14) (100 % sulphate sulfur) — allowed to increase grain yield by 24—26% compared to the traditional approach of farmers (100% elemental sulfur). At the same time, the same amount of nutrients was introduced into the soil — N100P40K40S28.

The maximum increase in gross revenue relative to the control (N100), equal to 158.9 US dollars/ha, was obtained with the following system of mineral nutrition of corn:

- NP(S) 20:20(14) before sowing;
- potassium chloride before sowing;
- urea in top dressing randomly in the phase of 4 leaves.

2.7. Technical oilseeds

Winter rapeseed

Lithuania

The study of fractional application of the recommended dose of phosphorus in the composition of a liquid complex fertilizer for the cultivation of winter rapeseed was carried out on the sod-podzolic sandy loam soil of Lithuania.

In the field experiment, with high soil potassium availability, the following strategies for feeding winter rapeseed were used:

- combination of macro- and meso-elements (nitrogen, phosphorus and sulfur) is a necessary condition for obtaining high seed yields;
- fractional application of the recommended dose of phosphorus in two doses as part of a liquid complex fertilizer (before sowing + foliar top dressing) is more effective than a single application as part of a granular fertilizer.

In this experiment, the following conclusions were made:

When growing winter rapeseed in 2020 on sod-podzolic sandy loam soil with good availability of mobile phosphorus and high availability of mobile potassium, the best seed yield (3.11 t/ha) was obtained through the use of a fertilizer application system with fractional phosphorus application (in kg/ha N135P46+10S60):

- LCF, NP 11:37 sprayer for pre-sowing cultivation;
- LCF, NP 11:37 — foliar top dressing in the BBCH 20 stage (the beginning of the development of lateral shoots);
- ammonium sulfate in top dressing randomly in the BBCH 20 stage;
- ammonium nitrate in top dressing randomly in the BBCH 20 stage.

The above-mentioned system of applying fertilizers for winter rapeseed with the transfer of 10 kg of P_2O_5 / ha to fertilizing allowed to receive additional income equal to 279.5 euros / ha, relative to the standard approach, which provides for the introduction of granular phosphorus-containing fertilizer in a full dose of phosphorus before sowing. The cost of harvesting the crop increase was not taken into account.

3. Risk assessment and management

There is no doubt that there is a need to assess risks of various nature arising from the change of previously established traditions in the fertilizer production and logistics markets. Along with the risks to public health, the risks of depletion of soil fertility with a decrease in the use of fertilizers or abandonment of them have to be assessed.

Today, more than 170 million tons of mineral nitrogen fertilizers are used annually in world agriculture [10]. In 2010, the total amount of nitrogen coming from fertilizers, biological nitrogen fixation (BPA) by leguminous crops, atmospheric precipitation and manure amounted to 174 million tons N, but only 74 million tons N was detected in the collected products [38]. Most of the remaining nitrogen is lost from agricultural land to the environment, where it harms sensitive ecosystems, reduces air quality and contributes to climate change, which leads to costs for biodiversity, fisheries, human health and social infrastructure [52—68].

Anthropogenic reactive compounds are easily absorbed by plants and other organisms, and the need for nitrogen fertilizers has led to a doubling of N fluxes in its global cycle. This is no longer safe, because it changes the entire biosphere as the habitat of humanity. The United Nations (UN) Environment Program has identified excessive reactive N as one of the five emerging threats facing the planet [63—65], so the Fourth UN Environment Assembly (March 2019) adopted the resolution “Sustainable Nitrogen Management”.

Nitrogen fertilization is a “double-edged sword” that provides food security for most of humanity, while having a huge negative impact on the environment and human health [62]. Globally, fertilizer nitrogen is also the largest source of nitrous oxide (N_2O), which has a powerful (~300-fold) global warming potential compared to carbon dioxide and is a long-lived greenhouse gas, whose concentration in the atmosphere increased by 0.8 parts per billion (ppb) per year from 300 ppb in 1980 to 332 ppb in 2020 [64, 68].

Currently, there is an increasing interest in assessing various factors associated with increasing the efficiency of nitrogen use. First of all, this is due to the increase in the use of mineral nitrogen fertilizers, which has now reached more than 170 million tons. The amount of organic fertilizers and compost used is also growing, which are also a source of nitrogen introduced into agroecosystems. The negative environmental consequences of the irrational use of nitrogen fertilizers are characterized by the accumulation of nitrate and nitrite nitrogen in drinking water sources, in crop production and an increase in the unbalanced intake of N_2O into the atmosphere due to the denitrification process. These ecological consequences are recorded in almost all soil-climatic zones. The possibility of assessing environmental risk using methods and techniques of agrogeochemistry is shown. The quantitative assessment of various articles of the agrogeochemical nitrogen cycle makes it possible to determine the possibilities of eliminating excessive anthropogenic pressure on them. First of all, this is due to the optimization of doses of nitrogen fertilizers, for example, based on the determination of the nitrogen mineralizing ability of soils, and a corresponding decrease in the content of nitrogen in various components of agroecosystems subject to denitrification and leaching. The accumulation of nitrates in plant products also decreases [2, 69].

Conclusion

Global food needs are projected to double by 2050 to feed 9 billion people, and the question facing agriculture is whether this is possible. These goals will face increasing climate variability and an increase in extreme temperatures and precipitation in all parts of the world [70—72], as well as a decrease in the volume and quality of the land resource base [73—77]. There are many problems to face; however, first of all it is necessary to focus on the interaction of genetics × environment × management (G × E × M), where management means primarily the use of a sufficient amount of mineral fertilizers in precision agriculture [78]. This opens up the potential to feed 9 billion people. Understanding and quantifying the required crop yields provide the basis for evaluating the planned means and methods of achieving progress in this direction, and the task will be to determine the most effective and efficient way to increase yields through more efficient use of water and nutrients from fertilizers and soil. A more appropriate approach to increasing the potential would be to increase the actual yield rather than increase the potential yield. The actual increase in yields and overall productivity can be provided by management systems focused on increasing land productivity, since our ability to expand available land resources is not a viable option.

In addition, it is necessary to pay great attention to the problem of increasing the efficiency of the use of mineral fertilizers due to the expected reduction in their production, or, for the time being, stagnation. Thus, the EU, within the framework of the Farm-to-Fork strategy, aims to reduce the loss of plant nutrients by at least 50% by 2030 and reduce the use of fertilizers by 20% [83]. Although this article focuses on improving the efficiency of the use of nitrogen fertilizers, with an assessment of the values of NUE, this approach can and should also be used for phosphorus and potash fertilizers. It is necessary in the future to pay more attention to the evaluation of the values of the phosphorus use efficiency, PhUE, as well as similarly for potash fertilizers with an assessment of the potassium use efficiency, PUE. In the case of phosphorus, we should talk about sustainable phosphorus management, in particular, meaning, for example, fractional application and use of fertilizers that do not contain high concentrations of heavy metals. This is described in the Case studies section. When using potash fertilizers, the measure of evaluating the effectiveness of their use can be an assessment of the potash potential of soils, which will allow assessing the potash regime of soils and optimizing the doses of potash fertilizers.

Under these conditions, it is impossible to overestimate the role of mineral fertilizers, in the production of which it is necessary to use, as mentioned above, methane — a source of carbon dioxide and hydrogen, as well as an energy source [79—82].

Without any doubts, the fundamental role of mineral fertilizers in food security will only increase in future and hopefully these review will form a holistic view of readers on the problem of global and regional food safety and the basic approaches for its solution using mineral fertilizers.

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Authors

Bashkin Vladimir N.: Doctor of Biological Sciences, Professor, Chief Researcher of the Institute of Physico-Chemical and Biological Problems of Soil Science of the Russian Academy of Sciences
Number of publications: more than 400
Research interests: geoecological risks, gas industry, biogeochemistry
ResearcherID: J-4621-2018
Scopus Author ID: 7005340339
Contact information:
Address: Institutskaya str., 2, Pushchino, Moscow region, 142290, Russia
vladimirbashkin@yandex.ru

Alekseev Andrey O.: Corresponding Member of the Russian Academy of Sciences, Doctor of Biological Sciences, Chief Researcher, Head of the Department, Head of the Institute of Physico-Chemical and Biological Problems of Soil Science of the Russian Academy of Sciences
Number of publications: about 200
Research interests: soil science, soil mineralogy, biogeochemistry, geochemistry, environmental magnetism, soil organic matter, soil evolution, paleosols, paleogeography, Pleistocene, Holocene, Paleozoic
Scopus ID: 7202889447
ResearcherID: L-1162-2014
ORCID: 0000-0001-5158-4454
AuthorID: 58747
Contact information:
Address: Institutskaya str., 2, Pushchino, Moscow region, 142290, Russia
alekseev@issp.serpukhov.su

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