Research article

https://revistas.unal.edu.co/index.php/refame

Revista Facultad Nacional de Agronomía

UNIVERSIDAD NACIONAL DE COLOMBIA

Influence of fertilization on the crop rotation productivity and the balance of essential nutrients in the soil

Influencia de la fertilización en la rotación de cultivos de campo sobre su productividad y el equilibrio de nutrientes esenciales en el suelo

https://doi.org/10.15446/rfnam.v75n2.98290

Hrygorii Hospodarenko[1], Vitalii Liubych[1]*, Olena Oliinyk[1], Iryna Polianetska[1] and Taras Silifonov[1]

ABSTRACT

Keywords:
Luvic chernozem
Nitrogen
Phosphorus
Potassium

The article shows the influence of different rates and combinations of mineral fertilizers on the balance of essential nutrients in the four-field crop rotation (winter wheat, corn, spring barley, and soybean) during eight years in the context of incorporation into the soil or removal of a non-commercial part of the yield of the field. The stationary field experiment was performed on the black podzolized heavy loamy soil of the Right-Bank Forest-Steppe. The experiment scheme included 11 variants of combinations and separate applications of mineral fertilizers as well as control variants without fertilization. It has been established that in the annual removal of nutrients together with grain harvest nitrogen makes up the biggest share (64.4–149.9 kg ha^{-1}), then phosphorus – 21.1–51.4 kg ha^{-1} depending on the fertilizing in the crop rotation. The variant of the experiment $N_{110}P_{60}K_{40}$ provides the optimal intensity of the balance of nitrogen, phosphorus, and potassium (103, 122, and 111%, respectively) when a non-marketable part of the yield is left for fertilizing in the field. When this part of the yield is removed from the field there is a deficit balance of nitrogen, phosphorus, and potassium with the intensity (76, 76, 61%, respectively) even in the variant with the annual average application of $N_{110}P_{60}K_{80}$. The use of non-marketable agricultural products in crop rotation for fertilization and the average annual application of $N_{110}P_{30-60}K_{40-80}$ allows compensation for the losses of nitrogen 24%, phosphorus 33%, and potassium 71%.

RESUMEN

Palabras clave:
Chernozem lúvico
Nitrógeno
Fósforo
Potasio

El artículo muestra una influencia de los primeros ocho años de un experimento a largo plazo de diferentes dosis y combinaciones de fertilizantes minerales sobre el equilibrio de nutrientes esenciales en la rotación en cuatro años de cuatro campos (trigo de invierno, maíz, cebada de primavera, soja) en el contexto de la incorporación en el suelo o la eliminación de la parte no comercial del rendimiento del campo. El experimento de campo se implantó en el suelo negro podzolizado pesado franco de las Bosques-Estepas de la orilla derecha. El esquema experimental incluye 11 variantes de combinaciones y aplicación separada de fertilizantes minerales, así como la variante de control sin fertilización. Se ha establecido que en la eliminación anual de nutrientes junto con la cosecha de granos, el nitrógeno constituye la mayor parte (64,4–149,9 kg ha^{-1}), luego el fósforo – 21,1–51,4 kg ha^{-1} dependiendo de la fertilización en la rotación de cultivos. La variante del experimento $N_{110}P_{60}K_{40}$ proporciona la intensidad óptima del equilibrio de nitrógeno, fósforo y potasio (103, 122 y 111%, respectivamente) cuando una parte no comercializable del rendimiento se deja para fertilización en el campo. Cuando esta parte del rendimiento se elimina del campo, hay un déficit de nitrógeno, fósforo y potasio con la intensidad (76, 76 y 61%, respectivamente) incluso en la variante con la aplicación media anual de $N_{110}P_{60}K_{80}$. El uso de productos vegetales no comercializables de la rotación de cultivos para la fertilización y la aplicación media anual de $N_{110}P_{30-60}K_{40-80}$ permite compensar las pérdidas de nitrógeno en un 24%, fósforo en un 33% y potasio en un 71%.

[1] Uman National University of Horticulture, Uman, Ukraine. hospodarenko@gmail.com, LyubichV@gmail.com, lenauman@gmail.com, polyanetska@ukr.net, silifon83@ukr.net

* Corresponding author

Received: February 17, 2022; Accepted: April 11, 2022

Rev. Fac. Nac. Agron. Medellín 75(2): 9919-9928. 2022

ISSN 0304-2847 / e-ISSN 2248-7026

Nowadays the application of fertilizers is one of the most significant parts of agricultural technologies (Šimanský and Jonczak, 2019; Novak *et al*., 2019). A long-term application of fertilizers increases the radioactivity of the soil due to the content of ^{40}K and ^{226}Ra, however, this radiation is safe for human health (Hospodarenko *et al*., 2019). Besides, the application of fertilizers improves the quality of the grain, which is important for the production of high-quality products (Hospodarenko and Liubych, 2021; Osokina *et al*., 2020; Petrenko *et al*., 2017).

The problem of soil fertility in Ukraine remains acute because of the large areas of plowed lands, drastic increase of landowners and land users, whom do not follow science-based crop rotation, and soil tillage, which leads to degradation processes: over-compactness, erosion (Medviediev *et al*., 2018). In addition to this, the economic crisis caused a considerable decrease in the level of using mineral fertilizers, which worsen the problem of soil fertility preservation.

Therefore, this involves the issue of developing such fertilizing systems for different soil and climate conditions that provide high productivity of plants with the simultaneous restoration of soil fertility. That is the reason why it is necessary to develop energy-saving and cost-effective fertilizing systems with high ecological effects, whose application would be expedient not only for large successful but also for small-size farm enterprises.

The efficiency of using organic and mineral fertilizers under field crops on the black soils was researched in the previous studies (Hamayunova and Filipiev, 1997; Ivanina, 2012; Lopushniak, 2015; Poliovyi, 2007). However, these experiments were carried out, as a rule, in different soil and climate conditions, under different structures of 8-12-field crop rotations and with the removal of straw from the field to meet the needs of animal breeding, and under a low level of yielding capacity of crops.

At present, most farms are involved in plant production, and as a result, manure is absent in the circulation of nutritional substances. Their specialization, change in farmland structure and nature protection aspects influence the intensity and approaches of crop fertilization system. The application of agricultural technologies that provide renewal of soil fertility and prevent pollution are of primary importance among the measures aimed at achieving a neutral level of soil degradation in Ukraine (Baliuk *et al*., 2018).

It is especially important to establish regional parameters of nutrient balance considering the type of crop rotations and the level of their productivity as well as optimal saturation of arable land with organic and mineral fertilizers. The efficiency of using fertilizers depends on their application rates in the first place. When calculating the optimal rate of fertilizers attention should be paid to the biological properties of crops and the planned level of yielding capacity, climatic conditions and soil fertility, the level of agrotechnology, the succession of crops in the rotation crop, and their saturation with fertilizers, forms of fertilizers, the method and timing of their application, and other factors. Therefore, determining the doses of fertilizers is one of the complicated issues of the current agronomical science and practice (Marschner, 2012; Hospodarenko *et al*., 2019). In addition to this, it has been established that it is possible to achieve a high yielding capacity of crops under regular application of fertilizers, and by adding considerably lower rates of fertilizers, which can be explained by the after-action of fertilizers applied under previous crops in the crop rotation (Šimanský, 2016).

Calculating the nutrient balance makes it possible to establish the direction of the processes in the system soil-fertilizer-plant, to determine the parts, surplus, or the deficit of certain nutritional elements of plants. Conducting such research in dynamics makes it possible to develop recommendations on the planned regulation of nutrient balance and humus in the soil (Bohdevych, 2006). Under a positive balance of nutrients, it is important to consider the necessity to increase soil fertility as well as the threat of pollution of the soils and water sources (Asif *et al*., 2019).

References provide the data about the expenses of nutrients on the formation of marketable products and the corresponding amount of non-marketable products, according to which is possible to determine the general need of a crop in nutrient elements for the formation of planned yields.

However, the relative removal of nutrients even in one crop changes considerably depending on the soil and climate conditions, the size of the yield, the correlation between marketable and non-marketable produce in the yield, the quality of yield, specific features of varieties and hybrids (Ivanina, 2012).

It is considered that to make balance calculations when non-marketable produce is not removed from the field, it is worth using the index of potassium removal only by the main produce. To calculate the rates of fertilizers for planned yields it is reasonable to use the data about the expenses of potassium on the formation of the unit of the main product with the account of the necessary amount of non-marketable produce (Klochko and Syryi, 2011). It can be explained by the fact that the requirement potassium of plants can be provided up to 50% from the supplies below plowed soil layers (Hrckova *et al.*, 2018).

Data dealing with the productivity of short-term field crop rotations on the black soils which, depending on the level of fertilizing, are not sufficient. The fraction of every crop in short-term rotations increases, which influences the use of nutrients in the soil and fertilizers. The common rule that the higher the rates of fertilizers are, the higher the yields of crops, is not relevant in the conditions of the energy crisis. Closer determination of quantitative features of the balance in the soil-fertilizer-plant system is relevant in different soil and climate conditions with the account of the rates of fertilizers and combination of nutrients with the intention of developing practical recommendations on the optimization of nutritional regime of the soil and increase the productivity and protect the environment.

Therefore, this research aimed to evaluate the balance of the main nutrients in the black podzolized heavy loamy soil in the Right Bank Forest-Stepp of Ukraine under different rates and combinations of mineral fertilizers in a short-term crop rotation when a non-marketable part of the yield is incorporated into the soil or removed from the field and to validate the optimal saturation with fertilizers to restore soil fertility and obtain stable yields.

MATERIALS AND METHODS

The stationary field experiment was carried out at the Uman National University of Horticulture (certificate of the National Academy of Agricultural Sciences No. 87) (Stationary field experiments of Ukraine, 2014) in the Right-Bank Forest Steppe of Ukraine with Greenwich geographical coordinates 48°46' of northern latitude and 30°14' of eastern longitude. The experiment was started in 2011. The following crops were cultivated in the four-field crop rotation: winter wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), spring barley (*Hordeum vulgare* L.), and soybean (*Glycine max* Moench.). The field experiment aims to establish the efficiency of the action of different types, rates, and proportions of mineral fertilizers on the yielding capacity and quality of grain and seeds of field crops, and fertility of the black soil. The scheme of the experiment includes 11 variants of combinations and separate applications of mineral fertilizers including the control variant without fertilizers (Table 1).

Table 1. Design of application of fertilizers in the experiment.

Variant of the experiment: average rates of nutrients in the crop rotation (kg active substance ha^{-1} per year)	Application of fertilizers in the crop rotation			
	Winter wheat	**Corn**	**Spring barley**	**Soybean**
Without fertilizers (control)	-	-	-	-
N_{55}	N_{75}	N_{80}	N_{35}	N_{30}
N_{110}	N_{150}	N_{160}	N_{70}	N_{60}
$P_{60}K_{80}$	$P_{60}K_{80}$	$P_{60}K_{110}$	$P_{60}K_{70}$	$P_{60}K_{60}$
$N_{110}K_{80}$	$N_{150}K_{80}$	$N_{160}K_{110}$	$N_{70}K_{70}$	$N_{60}K_{60}$
$N_{110}P_{60}$	$N_{150}P_{60}$	$N_{160}P_{60}$	$N_{70}P_{60}$	$N_{60}P_{60}$
$N_{55}P_{30}K_{40}$	$N_{75}P_{30}K_{40}$	$N_{80}P_{30}K_{55}$	$N_{35}P_{30}K_{35}$	$N_{30}P_{30}K_{30}$
$N_{110}P_{60}K_{80}$	$N_{150}P_{60}K_{80}$	$N1_{60}P_{60}K_{110}$	$N_{70}P_{60}K_{70}$	$N_{60}P_{60}K_{60}$
$N_{110}P_{30}K_{40}$	$N_{150}P_{30}K_{40}$	$N_{160}P_{30}K_{55}$	$N_{70}P_{30}K_{35}$	$N_{60}P_{30}K_{30}$
$N_{110}P_{60}K_{40}$	$N_{150}P_{60}K_{40}$	$N_{160}P_{60}K_{55}$	$N_{70}P_{60}K_{35}$	$N_{60}P_{60}K_{30}$
$N_{110}P_{30}K_{80}$	$N_{150}P_{30}K_{80}$	$N_{160}P_{30}K_{110}$	$N_{70}P_{30}K_{70}$	$N_{60}P_{30}K_{60}$

In the variant of the experiment with an average rate of nutrients in the crop rotation per hectare N110P60K80, the total (100%) compensation with fertilizers of average annual removal of the nutrients by the crops in the crop rotation is planned. The scheme of the experiment was developed in such a way that it could be possible to determine the opportunity to decrease the rates of certain types of mineral fertilizers. The placement of the variants in the experiment was successive. Performance of the experiment simultaneously on four fields provided annual data about the yielding capacity of all crops in the four-field crop rotation. Fertilizers application was replicated three times in the crop rotation deployed in space and time. The total area of the experimental plot was 110 m^2, and the accounting area was 72 m^2. Phosphorus (granulated superphosphate) and potassium (potassium chloride) fertilizers were applied during fall tillage, nitrogenous fertilizers (ammonium nitrate) during pre-sowing cultivation, and fertilizing of winter wheat.

The soil on the experimental plot is the luvic chernozem (World Reference Base for Soil Resources, 2014) heavy loamy soil on loess with 3.8% of humus content, pH_{KCl} – 5.7, the content of nitrogenous hydrolyzed compounds by the Cornfield method was 105 mg kg^{-1}, the content of mobile compounds of phosphorus and potassium by Chirikov method, was increased 106 mg kg^{-1} and 132 mg kg^{-1}, respectively.

Characteristics of genetic horizons of the luvic chernozem

He (0–42) – humus, slightly illuvial, dark-grey horizon with homogeneous humus content, dispersed fine-clodded structure, consolidated subsurface permeated with small roots and noticeable transition. Humus content was 3.8%, pH_{KCl} – 5.7.

Hpi (42–70) –slightly illuvial, dark-brown with the shade of parent material, small nut-like structure permeated with roots, with inhomogeneous humus content and noticeable transition. Humus content was 3.1%, pH_{KCl} – 5.9.

PIh (70–100) – slightly moistened illuvial horizon, dark yellow, nut-columnar structure with a transition to columnar, insignificant heterogenous. Humus content was 2.0%, pH_{KCl} – 7.0.

Pi(h) (100–120) – slightly illuvial, dark-yellow in color, with a prism-like structure, inhomogeneous insignificant humus content, and gradual transition to the parent rock, pH_{KCl} – 7.0.

Pk (120) – loess rock, brownish-yellow with fine texture, carbonates in the form of mold, veins, and individual clusters. The location of carbonates is at the depth of 120 cm, pH_{KCl} – 7.1.

Surface tillage was used (stubble disking after soybean harvesting was conducted twice) in the agrotechnology of winter wheat. Autumn tillage was applied on the corn, barley, and soybeans agrotechnology crops, including stubble peeling after stubble harvest and plowing at the depth of 28–30 cm

.

The amount of rainfall was by 1–4% higher over three years, it was 4–11% lower over the rest of the years compared to the average long-term index (Table 2). The air temperature was higher (2–7%) than the long-term average except for 2011.

The grain was harvested by combined harvesters. The accounting of the harvest of non-marketable produce was conducted by the method of the trial sheaf. Non-marketable part of the harvest of the crop rotation plants (straw, stems) was left in the field for fertilizing.

Table 2. Weather conditions throughout research (according to the Uman meteorological station)

Index	Year of the research								Long-term average index (1991–2020)
	2011	2012	2013	2014	2015	2016	2017	2018	
Rainfall, mm	593	584	555	608	527	509	524	601	586
Temperature (°C)	8.6	9.1	9.4	9.0	9.3	9.9	9.0	9.2	8.8

To simplify the calculations of nutrient balance the number of balance items was reduced both in terms of their supply and removal. Thus, the amount of nitrogen that comes into the soil from the atmosphere with precipitation and seeds is fixed by freely existing microorganisms was equal to its total expenses as the result of washing out, erosion and weathering. The total amount of phosphorus and potassium that come from the atmosphere and seeds was equal to the losses from erosion and washing out.

The content of nitrogen, phosphorus, and potassium in plant samples was determined after acid digestion (Yeshchenko *et al*., 2014). To evaluate the strength of connection among the investigated factors the coefficient of correlation was used according to the scale of R. E. Chaddock (Chaddock, 1952). Statistical data processing was carried out by using the software Microsoft Excel 2010 and STATISTICA 10.

RESULTS AND DISCUSSION

Crop rotation can work effectively only under conditions where substances and energy are returned to circulation, which creates optimal nutrition conditions for plants to obtain high yields. The research has shown that the regular application of different rates and combinations of mineral fertilizers in the field crop rotation improves considerably its productivity (Figure 1). The application of nitrogen-potassium, nitrogen-phosphorus, and complete mineral fertilizers influenced the productivity of the field crop. On average, the application of nitrogenous fertilizers increased the productivity of crops rotation by 1.5 times, phosphorus-potassium by 1.3 times, nitrogen-potassium by 1.7, nitrogen-phosphorus by 1.8 times, and complete mineral fertilizer by 1.9 times.

Long-term application of N_{55} increased the productivity of the crop rotation by 1.4 times compared to the variant

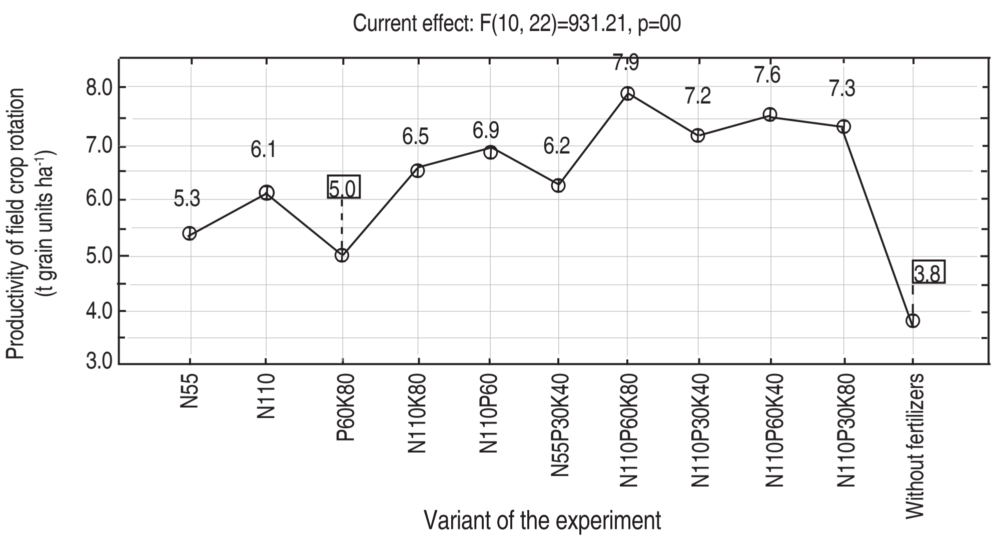

Figure 1. Productivity of field crop rotation under different fertilizers in the period from 2011 to 2018.

without fertilizers (Figure 2). Application of $N_{55}P_{30}K_{40}$ increased this index by 1.6 times compared to the plots without fertilizers and by 17% compared to the variant with N_{55}. Application of the doubled rate of nitrogen fertilizers increased the productivity of the crop rotation by 1.6 times compared to the variant without fertilizers. The productivity of the crop rotation, in this case, was 14% higher compared to the variant N_{55}. The application of complete mineral fertilizer ($N_{110}P_{60}K_{80}$) increased the productivity of the crop rotation by 2.1 times compared to the control and by 29% compared to the application of nitrogen fertilizers (N_{110}). Application of the complete mineral fertilizer (variants with the application N_{110} at the background of different proportions of phosphorus-potassium fertilizers) provided the highest productivity of the crop rotation (7.18–7.85 t ha^{-1} of grain units). Application of nitrogen-potassium and nitrogen-phosphorus fertilizers increased this index only by 6–14% compared to the variant N_{110}.

The productivity of the crop rotation under the application of phosphorus-potassium fertilizers was considerably lower compared to the other variants of fertilizing.

At the international conference in Uganda, the agreement was reached that the negative balance of nutrients is one of the main indexes of soil degradation (Bekunda and Manzi, 2003). The value of the maximum-permissible deficit of nutrition element depends on the content of its mobile compounds in soil and the level of productivity of a certain crop rotation. It is considered that for most types of soil there is no necessity for complete compensation of removed potassium on average during the rotation cycle (Prokoshev and Deriugin, 2000; Tobiašová *et al.*, 2013).

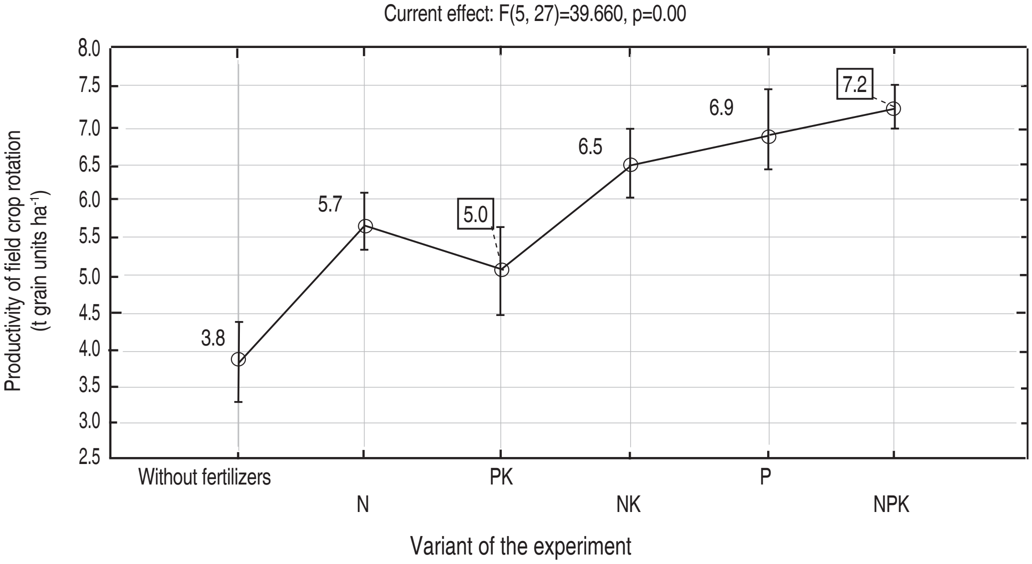

Figure 2. Productivity of field crop rotation under different fertilizers, their rates and proportions in the period from 2011 to 2018

Calculation of the nitrogen balance is used as the tool to evaluate the efficiency of fertilizers application and the corresponding ecological burden on the environment (Tarariko, 2011). The efficiency of its use in plant production is calculated as a share of nitrogen in the gathered harvest from its entering into the soil together with mineral and organic fertilizers, precipitation and the fixation of atmospheric nitrogen, etc. If this share exceeds 100%, the quality of the soil decreases.

Table 3 shows the balance of essential nutrients in the soil of the field crop rotation and its intensity. Taking into account the symbiotic atmospheric nitrogen fixed by soybean, the application of 110 kg of active substances of nitrogen fertilizers per hectare of crops rotation area provided 100–126% of the intensity of nitrogen balance on average during two rotation cycles depending on the experimental variant. It is necessary to mention that with the improvement of phosphorus and potassium nutrition of plants, the index of nitrogen balance intensity decreases. When the share of soybean is 25% in the structure of the crop rotation, the removal of nitrogen together with the main products by all crops was covered almost threefold (Hospodarenko *et al.*, 2019).

For the black soils in Moldova, the scheme was suggested that compensates for the removal of nitrogen by 26% due to organic fertilizers – manure and composts; 14% due to the fixation of atmospheric nitrogen by lentils, 48% due to the application together with mineral fertilizers. In this case, a 12% of nitrogen deficit is acceptable (Ivanina, 2012). The drawback of this approach is the coverage of nitrogen deficit due to manure by 26% which is explained by the decline in animal breeding.

The calculations showed that in the variant $N_{110}P_{60}K_{80}$ with 100% intensity of nitrogen balance during two rotation cycles in the crop rotation, its removal was compensated by the application of nitrogen fertilizers (73%) and by symbiotic nitrogen fixation by soybean (27%).

Thus, optimal nitrogen balance with 100–107% intensity was achieved when nitrogen was applied annually with mineral fertilizers 110 kg ha^{-1} in different combinations with phosphorus and potassium ($P_{30–60}K_{40–80}$).

Phosphorus balance in arable farming is of special practical value for the black soils (Nosko, 2017). Its circulation is simpler than that of nitrogen because its components are only soil and plants. According to Kramariov and Kramariov (2018), to increase the fertility of the soil it is necessary to reach 180–200% of the intensity of phosphorus balance, which is provided by the annual application of 60–80 kg ha^{-1}.

Table 3. Balance of essential nutrients in the soil of the field crop rotation and its intensity provided that a non-marketable part of the yield is left in the field in the period from 2011 to 2018.

Balance item	Variant of the experiment										
	Without fertilizers	N_{55}	N_{110}	$P_{60}K_{80}$	$N_{110}K_{80}$	$N_{110}P_{60}$	$N_{55}P_{30}K_{40}$	$N_{110}P_{60}K_{80}$	$N_{110}P_{30}K_{40}$	$N_{110}P_{60}K_{40}$	$N_{110}P_{30}K_{80}$
Nitrogen											
Supply (kg ha^{-1})	21	81	139	26	142	144	85	150	144	149	145
Removal (kg ha^{-1})	64	95	110	87	119	129	111	150	135	144	138
Balance (kg ha^{-1})	-44	-14	29	-61	24	15	-26	0	9	4	7
Balance intensity (%)	32	85	126	30	120	112	77	100	107	103	105
Phosphorus											
Supply (kg ha^{-1})	–	–	–	60	–	60	30	60	30	60	30
Removal (kg ha^{-1})	21	30	34	31	36	45	38	51	44	49	45
Balance (kg ha^{-1})	-21	-30	-34	29	-36	15	-8	9	-14	11	-15
Balance intensity (%)	–	–	–	194	–	133	79	117	69	122	67
Potassium											
Supply (kg ha^{-1})	–	–	–	80	80	–	40	80	40	40	80
Removal (kg ha^{-1})	17	23	26	24	31	32	29	38	33	36	35
Balance (kg ha^{-1})	-17	-23	-26	56	49	-32	11	42	7	4	46
Balance intensity (%)	–	–	–	336	261	–	137	212	121	111	232

However, there is an opinion that with the improvement of the phosphorus regime in black soils the rate of phosphorus fertilizers can be decreased because excessive phosphorus nutrition decreases the availability of some microelements to plants and the quality of agricultural produce.

In Belarus, the system of applying mineral fertilizers implies the returning of nutrients, compensating for their removal along with the harvest and provides a gradual increase of the content of mobile compounds of phosphorus and potassium to 200–300 mg kg^{-1} of soil. In this case, the application of phosphorus and potassium fertilizers should compensate by 100% the removal of these elements by the planned yielding capacity of crops on the soils with the content of mobile compounds of phosphorus and potassium lower than optimal value – 120, and on the soils with their content higher than optimal value by 50% removed together with the yields (Lapa and Tsybulko, 2018). Calculations have shown that alongside the improvement of mineral nutrition of plants due to the application of fertilizers the removal of phosphorus from the soil together with the yield increases more than two-fold (Table 3). The application of phosphorus fertilizers at the rate of 30 kg ha^{-1} at the background of $N_{55}K_{40}$ on average per ha^{-1} of crop rotation does not provide a positive balance of phosphorus. The intensity of phosphorus balance at the level of 117–133% was formed in the variants $N_{110}P_{60}$, $N_{110}P_{60}K_{40}$, and $N_{110}P_{60}K_{80}$. In the background of applications $N_{110}K_{40}$ and $N_{110}K_{80}$, according to this study, the balance of phosphorus is provided by the application of 49 and 51 kg ha^{-1} respectively.

Luvic chernozem has the most favorable potassium regime. In 70% of areas, the soils in Ukraine provide an increased and high level of nutrition for plants with potassium. To maintain a potassium regime, it is necessary to apply 35 kg ha^{-1} of arable soil annually together with fertilizers (Medviediev *et al.*, 2018). On the black soils of the Forest Steppe, the calculated rate of potassium fertilizers in crop rotations with the organic and mineral fertilizing systems could be reduced by 20%. In the areas with irregular rainfall, the return of removed potassium together with the yields on the black soils should be at the level of 40–60% (Hospodarenko *et al.*, 2019).

Table 3 shows that the balance of potassium in the crop rotation consists of the same parts as those of phosphorus. The removal of potassium together with the grain on average over two rotation cycles was insignificant (17.2–37.8 kg ha^{-1} of the area under crop rotation over a year) and increased two-fold under the application of the complete mineral fertilizer. The balance of potassium in all variants with the application of potassium fertilizers at the rates of 40–80 kg of active substance ha^{-1} formed positively with the intensity of 111–336%. It was the lowest in the variant $N_{110}P_{60}K_{40}$. A considerable part of potassium returns to the soil with non-marketable products (straw of winter wheat, spring barley, soybean, and leaf-stem mass of corn). This potassium is available to all crops in the crops rotation; therefore potassium fertilizers should be applied under potassium-filling crops on the podzolized black soil. Other scholars noted that a low deficit balance of potassium in field crop rotation is admissible and justified (Lapa and Tsybulko, 2018).

Considering the economic crisis, it is suggested to use the whole or the part of the non-marketable part of the yields as an alternative raw material for fuel. It is necessary to know how the balance of nutrients and soil humus is formed (Hospodarenko *et al.*, 2018). According to Lapa and Tsybulko (2013), in the five-field rotation in the Central Forest-Steppe of Ukraine 24–26% of nitrogen, 22–24% of phosphorus, and 33–35% of potassium return together with plant residues into the soil. When 4 t ha^{-1} of non-marketable produce is plowed in the chain soybean-oats-corn, it permits compensation for the expenses of nitrogen on the formation of the yield by 43%, phosphorus by 35%, and potassium by 90% and improves the increase of the crop yielding capacity by 15%.

Calculations have shown that when the non-grain part of the yield was removed from the field, there was a negative nitrogen balance in all variants of the experiment (Table 4). Thus, in the variant $N_{110}P_{60}K_{80}$, the removal of nitrogen was covered only by 76%. Even under the application of nitrogen fertilizers in rotation at the rate of 110 kg ha^{-1} the intensity of nitrogen balance made up 97%. When the non-marketable part of the yield was removed from the field the phosphorus balance was 30–68 kg ha^{-1} depending on the variant except the variant $P_{60}K_{80}$, where the balance was positive – 7 kg ha^{-1}. Under such an approach to the plant growing the rate of phosphorus fertilizers (60 kg ha^{-1}) in the composition of the complete mineral fertilizer should be increased by 25–30%. Potassium balance in the crop rotation when the straw, leaf-stem mass was removed from the field, was drastically negative with the intensity of 32–102% depending on the fertilizing variant. As a result, the removal of a non-marketable part of the yield from the field creates a deficit balance of the main nutrients even in the case when $N_{110}P_{60}K_{80}$ ha^{-1} is applied under crop rotation.

The application of non-marketable crop products of the crop rotation for fertilizing without additional application of mineral fertilizers compensates the expenses of nitrogen on the formation of the yield only by 19%, phosphate and potassium by 34 and 69% correspondingly. In the variant with $N_{110}P_{60}K_{80}$, these indexes constitute 24, 33, and 71%, respectively.

Hence, the non-marketable products eliminated from the field can increase soil erosion, deteriorate physical properties and decrease organic matter content. These variables can affect the dynamics of water and nutrients, and therefore crop yields.

Table 4. Balance of essential nutrients in the soil during the crop rotation and its intensity when non-marketable part of the yield is removed from the field in the period from 2011 to 2018

Balance item	Variant of the experiment										
	Without fertilizers	N_{55}	N_{110}	$P_{60}K_{80}$	$N_{110}K_{80}$	$N_{110}P_{60}$	$N_{55}P_{30}K_{40}$	$N_{110}P_{60}K_{80}$	$N_{110}P_{30}K_{40}$	$N_{110}P_{60}K_{40}$	$N_{110}P_{30}K_{80}$
Nitrogen											
Supply (kg ha^{-1})	21	81	139	26	142	144	85	150	144	149	145
Removal (kg ha^{-1})	80	121	144	109	156	170	143	196	178	190	181
With main products	64	95	110	87	119	129	111	150	135	144	138
With non-marquetable products	16	26	34	22	37	41	32	48	42	45	43
Balance (kg ha^{-1})	-59	-40	-5	-83	-13	-26	-58	-48	-33	-41	-36
Balance intensity (%)	26	67	97	24	92	85	59	76	81	78	80
Phosphorus											
Supply (kg ha^{-1})	–	–	–	60	–	60	30	60	30	60	30
Removal (kg ha^{-1})	37	56	68	53	73	86	70	99	90	94	88
With main products	21	30	34	31	36	45	38	51	48	49	45
With non-marquetable products	16	26	34	22	37	41	32	48	42	45	43
Balance (kg ha^{-1})	-37	-56	-68	7	-73	-16	-40	-39	-30	-34	-58
Balance intensity (%)	–	–	–	113	–	70	43	61	33	64	34
Potassium											
Supply (kg ha^{-1})	–	–	–	80	80	–	40	80	40	40	80
Removal (kg ha^{-1})	56	78	90	79	105	110	99	132	115	124	121
With main products	17	23	26	24	31	32	29	38	33	36	35
With non-marquetable products	39	55	63	55	74	79	70	94	82	88	87
Balance (kg ha^{-1})	-56	-78	-90	1	-25	-103	-59	-52	-75	-84	-41
Balance intensity (%)	–	–	–	102	76	–	40	61	35	32	66

CONCLUSIONS

In agricultural removal of the nutrients with the grain yield in crop rotation (winter wheat, corn, spring barley, soybean) the largest part is made up of nitrogen (64.4–149.9 kg ha^{-1}), phosphorus – 21,1–51,4 kg ha^{-1} depending on the rates and combinations of mineral fertilizers. From agrochemical and ecological approaches when a non-marketable part of the harvest is left on the field the best balance of nutrients in the crop rotation is formed in the variant $N_{110}P_{60}K_{40,}$ which provides the balanced intensity of nitrogen, phosphorus, and potassium 103, 122, and 111%, respectively. When the non-marketable part of the yield is removed from the field there is a deficit balance of nitrogen, phosphorus, and potassium with the intensity of 76, 76, and 61% even in the variant with the average annual application of $N_{110}P_{60}K_{80}$. The application of non-marketable crop products in the crop rotation for fertilizing in the variant $N_{110}P_{60}K_{80}$ makes it possible to compensate for the losses of nitrogen for the formation of their yield by 24%, phosphorus by 33%, and potassium by 71%.

REFERENCES

Asif A, Jintong L, Lipu H and Guang HX. 2019. Effects of nitrogen rate and harvest time on biomass yield and nutrient cycling of switchgrass and soil nitrogen balance in a semiarid sandy wasteland. Industrial Crops and Products 136: 1–10. https://doi.org/10.1016/j.indcrop.2019.04.066

Baliuk SA, – Medviediev VV and Miroshnichenko MM. 2018.

Concept of achieven the neutral level of soil degradation in Ukraine. Brovin O.V., Kharkiv. 30 p.

Bekunda M and Manzi G. 2003. Use of the partial nutrient budget as an indicator of nutrient depletion in the highlands of southwestern Uganda. Nutrient Cycling in Agroecosystems 67(2): 187–195. https://doi.org/10.1023/A:1025509400226

Bohdevych IM. 2006. Balance of mineral nutrition elements and soil fertility. In Agrochemistry and soil science (special edition) 18–25. https://doi.org/10.31073/acss

Chaddock RE. 1952. Exercises in statistical methods. Houghton, 166 p.

Hamayunova VV and Filipiev ID. 1997. Determination of fertilizer rates under crops under conditions of irrigation. Bulletin of agrarian science 5: 15–19.

Hospodarenko HM and Liubych VV. 2021. Influence of long-term fertilization on yield and quality of spring triticale grain. Research for Rural Development 36: 29–35. https://doi.org/10.22616/rrd.27.2021.004

Hospodarenko H, Prokopchuk I, Nikitina O and Liubych V. 2019. Assessment of the contamination level of a podzolized chernozem with nuclides in a long-term land use. Agriculture (Poľnohospodárstvo) 65(3): 128–135. https://doi.org/10.2478/agri-2019-0013

Hospodarenko H, Prokopchuk I, Prokopchuk S and Trus O. 2018. Humus content in a podzolized chernozem after a long-term application of fertilizers in a field crop rotation. In AgronomyResearch 16(3): 737–748. https://doi.org/10.15159/ar.18.080

Hrckova K, Mihalčík P, Žák Š, Hašana R, Ondreičková K and Kraic J. 2018. Agronomic and economic performance of genetically modified and conventional maize. Agriculture 64(2): 87–93. https://doi.org/10.2478/agri-2018-0009

Ivanina VV. 2012. Balance of nutrients depending on the fertilization in different crop rotations. Collection of research papers of the National Scientific Center “Institute of arable farming” 3–4: 26–33.

Klochko MK and Syryi MM. 2011. The problem of potassium in balance calculations. Bulletin of Kharkiv national university 2: 111–112. https://doi.org/10.35550/visnykagro2019.21

Kramariov SM and Kramariov OC. 2018. Change of the content of mobile phosphate forms on the black soils of arable lands compared to virgin land and financial mechanism of its improvement. Agrochemistry and soil science. Special edition: 173–174.

Lapa VV and Tsybulko NN. 2018. Problems of improving fertility and protection against degradation of lands in Belasus. Agrochemistry and soil science. Special edition: 74–82.

Lopushniak VI. 2015. Agrochemical and agroecological aspects of fertilization systems in the Western Forest-Steppe of Ukraine. Liga-Press, Lviv. 217 p.

Marschner P. 2012. Marschner’s mineral nutrition of higher plants. Third edition. Elsevier Academic Press, Netherlands. 684 p.

Medviediev VV, Plisko IV, Nakisko SH and Titenko HV. 2018. Soil degradation in the world, experience of its prevention and overcoming. Stylna tyohrafiia, Kharkiv. 168 p.

Nosko BS. 2017. Phosphorus in soils and agriculture of Ukraine. FOP «Brovin O. V.», Kharkiv. 476 p.

Novak L, Liubych V, Poltoretskyi S and Andrushchenko M. 2019. Technological indices of spring wheat grain depending on the nitrogen supply. In: Nadykto, V. (eds) Modern Development Paths of Agricultural Production. Springer, Cham. https://doi.org/10.1007/978-3-030-14918-5_73

Osokina N, Liubych V, Novikov V, Leshchenko I, Pryhodko V, Petrenko V, Khomenko S, Zorunko V, Balabak O, Moskalets V and Moskalets T. 2020. Effect of electromagnetic irradiation of emmer wheat grain on the yield of flattened wholegrain cereal. Eastern European Journal of Enterprise Technologies 6(11): 17–26. https://doi.org/10.15587/1729-4061.2020.217018

Petrenko V, Liubich V and Bondar V. 2017. Baking quality of wheat grain as influenced by agriculture systems, weather and storing conditions. Romanian Agricultural Research 34: 69–76. https://doi.org/2067-5720 RAR 2017-153

Poliovyi VM. 2007. Optimization of fertilization systems in modern arable farming. Volynski oberehy, Rivne. 320 p.

Prokoshev VV and Deriugin IP. 2000. Potassium and potassium fertilizers. Ledum, Moscow. 185 p.

Šimanský V and Jonczak J. 2019. Sorption capacity of sandy soil under long-term fertilisation. Agriculture (Poľnohospodárstvo) 65(4): 164–171. https://doi.org/10.2478/agri-2019-0017

Šimanský V. 2016. Changes in soil organic matter parameters during the period of 18 years under different soil management practices. Agriculture (Poľnohospodárstvo) 62(4): 149–154. https://doi.org/10.1515/agri-2016-0015

Stationary field experiments of Ukraine. 2014. Agrarian Science, Kyiv. 146 p.

Tarariko YO. 2011. Energy-saving agroecosystems. Evaluation and efficient use of agrarian resources potential of Ukraine (Recommendations on the example of the Steppe and Forest-Steppe). Dia, Kyiv. 576 p.

Tobiašová E, Šimanský V, Dębska B and Banach-Szott M. 2013. Soil structure and soil organic matter of selected soil types in different ecosystems. Agriculture 59: 1–8. https://doi.org/10.2478/agri-2013-0001

Yeshchenko VO, Kopytko PH, Kostohryz PV and Opryshko VP. 2014. The fundamentals of the research in agronomy. “Edelveis and K”, Vinnytsia. 332p.