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This work considers the problem of comparative assessment of crop rotations from the point of view of agroeconomic efficiency and environmental feasibility. It has been suggested that such an evaluation should be carried out in two stages. At the first stage, individual crops are assessed according to their productivity in grain units and the cost of production (agroeconomic indicators) and according to the balance of humus and basic nutrients (ecological indicators). At the second stage, each crop rotation with its own structure of crops is evaluated according to the specified criteria. Three options, or levels of fertilization, are subject to evaluation: without fertilizers, with the application of the first quintal of active substance, and with the application of environmentally justified fertilizer norms.
The publication is intended for managers of agricultural enterprises, specialists, farmers. It may be useful for masters and scientists, specialists in the field of agricultural production and land management.

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INTRODUCTION

The basis for designing any crop rotation is primarily biological constraints, which are fundamentally related to the aftereffects of the predecessor. These include factors such as diseases, pests, weeds, moisture availability, differentiation by soil layers, and specific elements of nutrient consumption, among others. Additionally, there are other constraints on the structure of crops in crop rotation. These include both external economic and internal organizational-economic factors. The former are determined by the market demand for crop production and the selling price, which often dictate the actual structure of sown areas, which does not always align with the biological characteristics of the crop. Internal organizational-economic requirements depend on the structure of crops in crop rotation from other sectors of the economy, such as livestock farming.

In general, it can be stated that for creating conditions for the sustainable development of crop production, a strict adherence to the biological conditions of forming the structure of sown areas in crop rotation should be a necessary condition, which, in our opinion, should be one of the conditions for leasing agricultural land. In any case, the implementation of crop rotation should not allow for a decrease in the natural fertility of the soils, and, if possible, ensure its increase. This, in turn, will ensure an increase in yield, which is formed at the expense of the natural fertility of the soils, and thus reduce the required rate of mineral fertilizers for forming the planned yield of agricultural crops.

The aim of the proposed research is to develop a methodology for the comparative evaluation of different crop rotations to select the optimal option based on necessary or specified criteria. In this regard, it seems appropriate to consider options without fertilizer application and with fertilizer application. The option without fertilizer is the baseline or background, characterizing the productivity of the crop rotation on soils of a specific natural and climatic zone. The option with fertilizer application characterizes their effectiveness on these soils with a certain structure of sown areas. Considering that the effectiveness of fertilizers decreases with increasing application rates, it is advisable to consider the effectiveness of the first centner of active substance of mineral fertilizers and such an amount that ensures the ecological feasibility of the level of crop yields.

It should be noted that the productivity of crop rotation depends both on the productivity of each crop in the rotation and on its share in the structure of sown areas. This, in turn, indicates the feasibility of conducting the research in two stages. The first should be considered a comprehensive assessment of the productivity of all main crops in the rotation, and the second an assessment of possible or specified crop rotation schemes depending on the structure of sown areas.

1. AGROBIOLOGICAL BASIS OF COMPOSING CROP ROTATIONS

The improvement of agricultural practices involves the implementation of measures that constitute a scientifically justified system. Among them, proper crop rotations hold significant importance, as they are the main and irreplaceable link, also they occupy a special place due to their various beneficial effects on soil fertility and agricultural crop yields.

Crop rotation makes it possible to develop agricultural crop cultivation technologies taking into account their mutual influence, as well as the aftereffects of each measure applied to the nearest predecessors. This is why the growth of agricultural culture can only be ensured by adhering to scientifically justified crop rotations that correspond to specific natural and climatic conditions and the specialization of agricultural production [3].

Based on crop rotations, systems for applying fertilizers, mechanical soil cultivation, and protecting crops from weeds, pests, and pathogens are created. The lack of systematic approach in these measures, without considering what was grown in the field in previous years and what will be sown in the following ones, leads to low efficiency and neglect of the fields. In crop rotations, the objective laws of agriculture are better revealed, and adherence to them allows for the regulation of the nutrient cycle in agriculture [11].

Considering the biological characteristics and the ability of field crops not only to utilize but also to actively restore soil fertility, crop rotation significantly affects factors of fertility such as nutrient and moisture supply, humus content, biological regime, physical properties, and the rate of detoxification of harmful substances entering the soil during its agricultural use. Scientifically justified crop rotation is a measure that, with almost no additional material costs, contributes to increasing the yield of various field crops, most of which negatively react to cultivation under monoculture or unchanged sowing conditions.

Moreover, crop rotation determines the agronomic strategy for increasing soil productivity and agricultural crop yields, defining and integrating all components of the farming system into a single complex. The systems of fertilizer application, mechanical soil cultivation, and other agronomic and reclamation measures depend on the specialization of crop rotations, the composition, and the sequence of crops. The agronomic role of crop rotation at various stages of agricultural development, especially under conditions of its intensification, stems from the overall task of scientific agriculture. According to K. A. Timiryazev and D. M. Pryanishnikov, this task consists of aligning the requirements of cultivated plants with the conditions of their cultivation. Under appropriate climatic conditions and natural soil properties, the evaluation of crop rotation depends on the impact of preceding crops and the measures taken for their cultivation (soil tillage, fertilization, etc.). It is known that this impact is not uniform. Therefore, certain differences in soil properties and fertility are created depending on the preceding crops. These differences must be taken into account when placing agricultural crops in fields, in other words, establishing scientifically justified crop rotation [14].

The properties of soils, even the most fertile ones, such as chernozems, do not always meet the needs of cultivated plants, especially their high-yielding varieties. Therefore, creating the necessary conditions for the growth of agricultural crops, rational use and protection of soils, preservation and enhancement of their fertility are the main tasks at all stages of agricultural development. Based on the generalization of experience regarding the impact on the balance and content of humus, German researchers divide agricultural crops into four groups:

1. Perennial forage crops on arable land with low-intensity soil cultivation enrich the soil with humus and nitrogen.

2. Annual legumes enrich the soil with nitrogen and do not deplete humus reserves.

3. Cereal crops – with minimal tillage intensity, they reduce the content of humus and nitrogen less than row crops.

4. Row crops grown under intensive cultivation significantly reduce the content of humus and nitrogen in the soil.

Oilseeds and specialty crops are classified into the first three groups according to their impact [4, 11].

All field crops, depending on their reaction and rotation in the crop rotation system, can be divided into the following groups: stable or self-compatible (rye, corn, yellow lupin, soybeans, millet, potatoes – in fields where nematodes are absent); labile, which negatively react to repeated sowings (wheat, oats, sugar beet, fodder beet, clover, alfalfa, peas, flax, sunflower, cabbage); and crop rotation-labile, which cannot be sown one after the other, for example, wheat after barley, oats after barley, and vice versa.

Depending on the reaction of plants to continuous cultivation in the field, all field crops are divided into three groups: 1) very sensitive (flax, sugar beet, sunflower, peas, yellow lupin, millet, clover), 2) moderately sensitive (some tolerate better – winter cereals, others worse – spring cereals, corn, buckwheat), and 3) less sensitive (potatoes, hemp, tobacco, rice, cotton) [13].

Long-term research by scientific institutions has addressed a number of issues related to the theory and practice of crop rotation in specific soil-climatic zones of Ukraine, namely: the location, duration of cultivation, compatibility, and the period of crop return in crop rotations, taking into account the requirements of intensive technologies, the degree of saturation of crop rotations with leading crops in farms of various production orientations, etc.

The National Scientific Center "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine" considers the following permissible concentration of crops in crop rotations: grain crops 60–80%, sugar beets 20–25%, corn 50–60%, hemp 50%, potatoes 30–50%, sunflower and flax 14–16% [24,27]. These limits may vary significantly (Table 1).

Table 1

Structure of sown areas taking into account scientifically substantiated crop rotations based on soil-ecological principles of farming for the future [4]

Natural and agricultural region	Structure of sown areas, %							
	cereals and legumes	industrial crops			potatoes and vegetables	fodder crops		black steam
		total	including			total	including perennial herbs	
			rapeseed / soybean	sunflower				
Polissya	35–80	3–25	0,5–4	0,5	8–25	20–60	5–20	–
Forest-steppe	25–95	5–30	3–5 / 2–4	5–9	3–5	10–75	10–50	–
Northern-steppe	45–80	10–30	10 / 1–2	10	up to 20	10–60	10–16	5–14
Southern-steppe	40–82	5–35	5–10	12–15	up to 20	up to 60	up to 25	18–20
Precarpathian	25–60	5–10	–	–	8–20	25–60	10–40	–

The recommended ratio of crops in crop rotation is not absolutely rigid. This primarily applies to crops such as corn, sunflower, rapeseed, etc. It is clear that the scientifically substantiated limitation of the areas of use of individual crops that most deplete the soil is designed to ensure the restoration and preservation of its fertility, reserves of nutrients and humus, and to prevent the spread of pests and pathogens of agricultural crops.

The duration of crop rotation depends on the crop that has the longest return period to the previous place of cultivation. Compliance with this requirement will allow the crop to be grown on the maximum possible area.

The scientific principles of crop rotation construction provide for the correct selection of predecessors and the optimal combination of single-species crops with compliance with the permissible frequency of their return to the same field (Table 2).

Table 2

Frequency of returning crops to their previous place of cultivation [22]

Crop	Years of returning culture to its previous place	
	Forest-steppe	Polissya
Winter wheat	2–3	2–3
Winter rye	1–2	1–2
Winter barley	1–2	1–2
Barley, oats	1–2	1–2
Buckwheat	1–2	1–2
Millet	3–4	3–4
Peas, vetch, chickpeas, soybeans, fodder beans	3–4	3–4
Spring and winter rapeseed	3–4	3–4
Sugar and fodder beets	3–4	3
Potatoes	1–2	1–2
Sunflower	7–9	–
Sainfoin	2–3	–
Clover	3–4	3–4
Alfalfa	3–4	3–4
Perennial grasses	3–4	3–4
Sudan grass	3	3
Sorghum	3–4	3–4
black steam	10	–
Corn, silage corn	0–5	0–5
Annual grasses	1–3	1–3

With such a construction of crop rotation, first of all, they perform the main biological function - phytosanitary and allow to reduce the volume of chemical plant protection products used as much as possible. [20, 22].

The process of agricultural specialization in leading countries began a long time ago and is steadily spreading in Ukraine. With the deepening of this process (the saturation of crop rotations with intensive crops, the introduction of new high-yielding varieties and hybrids, the increasing scale of fertilizer and chemical plant protection product application, and energy-intensive cultivation technologies), the system of fertility management becomes more complex, and the requirements for soils increase. They must not only provide crops with favorable water-air and nutrient regimes but also have a significant phytosanitary function, capable of preventing the formation of high concentrations of applied chemical compounds, etc.

Producers, in the pursuit of "quick" money, concentrate their efforts on producing the maximum amount of high-profit products. Thus, the issue of rational placement of intensive crops—such as sunflower, corn, rapeseed, and soybeans—is extremely relevant today. And although the "optimization" of their placement has not been fully studied, significant contradictions between the specialization of their production and natural factors already exist in some regions of Ukraine. In particular, the repeated or continuous cultivation of the most common crops today, corn and sunflower, leads to a noticeable decrease in their yield and an increase in the number of weeds, for example, specific species [18]. For instance, during the tasseling phase of corn in crop rotation, there were 30 weeds per 1 m^2, in repeated plantings—94, and in some years—281 pcs./m^2. Moreover, the cultivation of corn for 2–3 years was accompanied by the accumulation of wireworm larvae in the soil up to 13.5–16.8 pcs./ha, and the damage to plants by the stem borer and smut increased, with the remnants and roots of corn being the focal points. In sunflower plantings, if optimal return times to the previous cultivation site are not adhered to, parasitic weeds spread massively [4, 11].

With continuous cultivation of agricultural crops, a decrease in their yield and deterioration in the quality of the harvest are observed, which is most often associated not only with the increase in weediness of the crops and damage by pests and diseases but also with the one-sided use of soil nutrients and the accumulation of various toxic substances in the soil – products of the life activities of plants and microorganisms.

Scientific and technological progress and the growth of production-resource potential somewhat mitigate existing contradictions. Under conditions of optimal provision with fertilizers and pesticides, the use of disease-resistant varieties, biopreparations, and other plant protection means, the importance of crop rotation in terms of mineral nutrition, weed control, pests, and diseases is diminished, and the possibility of repeated cultivation of crops increases.

The main criterion for the feasibility of crop rotation is sometimes moisture provision due to changing climatic conditions to more arid ones. The solution to the problem of regulating the water regime can be achieved through technical means, particularly the use of irrigation.

Regarding biological factors (such as soil biota activity, humus, and phytotoxic regimes of the soil), with the deepening of specialization, they become more difficult to manage, and therefore significantly limit land productivity [9].

If most limiting factors can be eliminated by various means, the only question is the cost-effectiveness and environmental safety of applying products and technologies, then an insurmountable obstacle to deepening the specialization of crop rotations is biological soil fatigue due to the accumulation of pathogens in the soil. Soil fatigue usually occurs with continuous sowing of certain crops and leads to a significant decrease in yield. Known examples include flax fatigue, beet fatigue, sunflower fatigue, clover fatigue, and others. Agronomic science constantly pays attention to identifying the causes of soil fatigue. It has been established that there are many common causes, but specific ones have also been identified for individual crops: for flax fatigue – the spread of fungal diseases, particularly fusarium; for beet fatigue – the spread of nematodes; for clover fatigue – the depletion of soil in phosphorus and potassium. However, these do not exhaust the causes of soil fatigue: even with the elimination of the mentioned causes, yields remain lower with continuous cropping than with scientifically justified crop rotation [3].

Currently, the problematic factors that prevent the avoidance of scientifically grounded crop rotation without significant costs include the development of sugar beet nematodes, root rot, sunflower broomrape, and others. If continuous cultivation of crops leads to the accumulation of specific pests, production costs significantly increase due to the use of insecticides, and the ecological risk rises even more due to their toxicity [11].

One of the effective measures to eliminate the negative consequences of continuous cropping can be considered intercropping, which is placed between two main crops in the crop rotation and creates a crop rotation link [4].

In the case of simplifying crop rotations to 3–4 fields, it is necessary to maximize the inclusion of intermediate green manure crops to restore the biological and agro-physical factors of fertility in order to mitigate the phenomena of allelopathic soil fatigue, which significantly reduces the need for the application of pesticides and other agrochemicals [11, 8].

Modern research has established that sideration is effective against plant diseases due to the increased activity of saprophytic microorganisms, which are antagonists of pathogens such as flax fusarium and potato rhizoctonia. The fungicidal action of sideral crops such as oats, mustard, oilseed radish, winter rye, buckwheat, phacelia, and sideral mixtures is high.

Green manuring is an effective factor in the interaction of biotic and abiotic processes that transform organic matter with the help of soil microflora into compounds that are available for plant uptake. The organic matter of legumes and "young" green manures is characterized by a narrow C:N ratio (1:20), which leads to intensive mineralization of phytomass and, consequently, a higher percentage of soil nutrient availability at the initial stages of cultivated plant development [6].

The root system of green manures, penetrating the soil layer, interacts with it, ensuring the uniform distribution of organic matter and preventing the development of erosion processes. At the same time, the main agro-physical indicators of the soil improve, and the so-called "plow sole" is destroyed, which ultimately enhances the utilization of essential factors for plant life [16].

To achieve an effective result, cover crops in intercropping should meet the following requirements:

a) accumulate sufficient vegetative mass (at least 100–150 c/ha) over a short growing season (40–60 days) with a sum of effective temperatures of 800–1000 °C and moisture availability at the level of 120–200 mm of precipitation;

b) be cold- and frost-resistant (easily withstand temperature drops in the autumn period);

b) have a high seed multiplication ratio (1: 40–60), meaning the seeds should be inexpensive.

First and foremost, cruciferous crops meet these requirements – winter and spring rapeseed, oil radish, white mustard, brown mustard, spring and winter canola, as well as winter rye, buckwheat, phacelia, vetch, and mixtures of these crops.

Domestic and foreign experience shows that the use of green manures in intermediate crops allows for scientifically grounded crop rotation with various biological and production characteristics. Under such conditions, all the main tasks outlined for growing crops in crop rotations are achieved: replenishing sources of organic matter and nitrogen in the soil; reducing non-productive moisture and nutrient losses by decreasing infiltration processes from the upper soil layer, thereby increasing the efficiency of precipitation, fertilizers, and chemical ameliorants; slowing down erosion processes, reducing weediness of crops, and in some cases, fungal diseases of cultivated plants; enhancing biological activity and improving the structural condition and composition of the soil [8].

Thus, summarizing the above, it should be noted that when the structure of sown areas reaches the maximum permissible limits of crop saturation, contradictions arise between crop rotation and the specialization of agriculture, which can intensify. Therefore, adherence to crop rotations remains one of the mandatory factors that ensure the most rational use of arable land, material, and labor resources. They are the organizational and territorial basis of sustainable agriculture, and their violation and neglect of elementary requirements for crop rotation, soil, and plant biology lead to soil fertility loss and reduced crop productivity, causing various environmental hazards.

1.1. Environmental, agronomic and economic factors of crop rotation.

Crop rotation is one of the categories used by every agronomist in daily practice.

No managerial decision concerning the cultivation of agricultural crops is made without considering its features: from the selection of agrotechnics, fertilization, and plant protection to the preparation of the seedbed for the next crop.

The sequence of crop placement on a specific land plot depends not only on soil quality indicators or optimal nutrient cycling ratios for achieving high productivity.

Today, specialists' deep knowledge in mineral nutrition and chemical protection systems has led agribusiness owners to choose crop rotations based solely on economic profit, often neglecting ecological standards.

Therefore, we will try to justify the various preconditions and consequences of such a choice.

Scientists, practitioners, and market experts share similar conclusions regarding the direction of crop rotation choices: from livestock-oriented systems to economic egocentrism.

The understanding that restoring the livestock sector at its former scale and structure in the next 10 years is unrealistic, along with the achievement of highly intensified crop production technologies, has led to a shift from 8–10-field rotations to 4-field or, at best, 6-field ones.

Thus, the choice has been made, and the only reason behind it is a managerial (or rather, purely economic) necessity.

This is confirmed by the structure of sown areas in Ukrainian agricultural enterprises over the past four decades (Table 3).

Table 3

Sown areas and share of major crops by years

Sown areas, million ha				Agroclimatic zone	Share of major crops*, %			
1990	2000	2010	2020		1990	2000	2010	2020
6,9	5,8	5,7	6,0	Polissya	38,6	32,2	49,1	75,4
17,9	15,0	14,9	15,5	Forest-steppe	52,8	50,8	75,6	85,8
7,6	6,4	6,3	6,5	Steppe	58,7	68,4	98,1	94,4
32,4	27,2	26,9	28,0	Ukraine	51,1	50,9	75,2	85,6

**: major crops include wheat, barley, corn, pulses, sunflower, soybeans and rapeseed*

The table shows the scale of cultivation of seven main crops (those sown on more than 1 million hectares, except for grain legumes, which cover 0.7 million ha) across various agro-climatic zones.

A general trend should be noted:

The situation has changed drastically over three decades—while the share of these selected crops was 51.1%, it has now reached 85.6%. This confirms earlier conclusions about the prioritization of certain crops.

The first decade can be characterized as a period of complete uncertainty, chaotic reform of agricultural enterprises, and mass land abandonment (minus 5 million hectares of sown area).

The 2000s were marked by the introduction of market mechanisms, the creation of entrepreneurial structures, and Ukraine’s entry into international markets, which fueled increased demand for agricultural products. The third decade can be described as the formation of a comprehensive agricultural business system with significant capital (including foreign) investment, intensification of cultivation technologies, a sharp rise in productivity, and favorable price dynamics on the markets for major crops.

All of this has led Ukrainian farmers to choose high-profit crops, primarily from the industrial group—sunflower, rapeseed, and soybeans, as well as grain maize.

Cereal grains remain at the top as strategic food crops and key predecessors in crop rotations.

Thus, in summary, the modern crop rotation system in Ukraine looks as follows: sunflower – wheat (barley) – rapeseed (soybeans, grain legumes) – maize for grain, in varying sequences but with a clear trend toward monoculture, ranging from 75.4% in the northern regions to 94.4% in the southern regions.

Looking at the indicators of the last decade, we can conclude that such managerial decisions by domestic agricultural producers regarding crop rotations, though based on complex factors, are purely tactical and driven primarily by economic considerations.

To confirm these statements, let us consider the following diagram (Figure 1). The factors influencing both the choice of crop rotations and the overall development of the sector are systematized into three groups: ecological, agrotechnical, and economic.

The specified order is significant, as farmers work with a unique means of production—land—and dependency on natural and climatic conditions remains high. This is clearly reflected in recent outcomes in the agro-industrial complex. The second group of factors—agrotechnical—has been mastered by professionals, resulting in truly impressive achievements: rapid advancements in machinery, diverse cultivation technologies, and efficient use of chemical industry innovations.

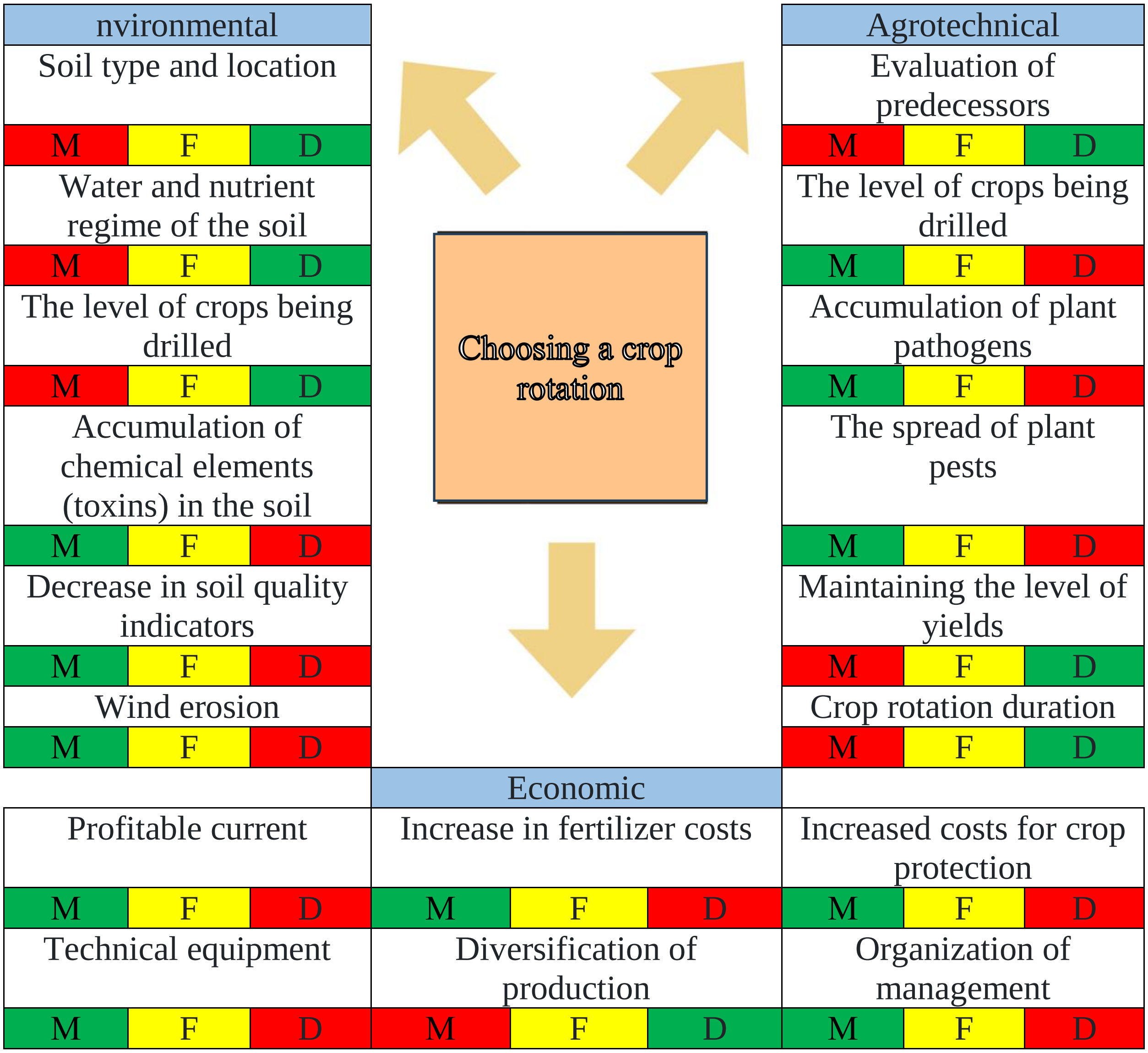

Figure 1. Prerequisites for choosing a crop rotation system and structure

Notes:

1) M - monoculture crop rotation (or close to it: 2-3 crops); F - fixed crop rotation (conditionally stable set of 4-5 crops); D - dynamic crop rotation (set of 6-8 crops with a combination of grasses);

2) colours determine the level of influence on the indicator: red - the least (worst), yellow - medium, green - the most (best)

In this coordinate system, the economic group of factors is the last on the list, but according to economic logic, it is the first. And there's no arguing with that, since farming is a profit-making business.

This means that an agrarian cannot be a philanthropist and only monitor the state of the environment in which he or she operates. These are functions inherent in the state, which is a regulator with powers and responsibilities to facilitate business and monitor compliance with legislation, including environmental legislation.

Currently, the effectiveness of compliance with land and environmental laws in Ukraine is low. In particular, according to the Resolution of the Cabinet of Ministers of Ukraine No. 164 dated 11.02.2010, the permissible standards for the frequency of crops cultivation on the same field are: for barley - not less than one year; for winter wheat - not less than two years; for corn in crop rotation - for 2-3 years in a row; for legumes, rape - not less than 3 years; for sunflower - not less than 7 years.

In practice, however, not all farms observe this frequency. Of course, it is difficult to blame all producers for absolute non-compliance with this resolution, the Land Code of Ukraine (which also contains several restrictions), or scientific recommendations. Most of them consider the opinions of experts (including international private entities) and try to balance economic and agrotechnical factors.

Such management is tactically short-term. As long-term monitoring studies of the condition and structure of Ukrainian soils continue to be conducted, usually by state research institutions of the relevant profile. Also, private agricultural enterprises have started to conduct surveys of cultivated land to better understand what the land and plants “need”.

Over the past 30 years, the average humus level in Ukraine has decreased by 0.12 units (from 3.28 to 3.16). At first glance, this decline seems insignificant. But this is not the case, as it will take 25-30 years to restore 0.1 unit of humus, if measures are properly implemented and excessive economic activity is limited. It is worth emphasizing here that the share of land with high levels of humus decreased by 4.7% (from 24.4 to 19.7) over the period under review, while the share of land with medium levels increased by 3.4% (from 24.0 to 27.4). The survey of more than 16 million hectares of land revealed another peculiarity - low content of macronutrients in soils -

an average of 105 mg/kg of nitrogen, 110 mg/kg of phosphorus and 120 mg/kg of potassium. Except for the last element, other indicators are low or average. Despite the high levels of micronutrients, the situation with soil condition can be characterized as a negative trend.

Therefore, all decisions taken to reduce the number of crops in the crop rotations of Ukrainian farmers, even if they are economically and agronomically justified, are justified only in terms of achieving tactical results over several years. The task of scientists is to develop a strategy for the development of agrarian business and the land use system that would satisfy all participants: business, the state, and consumers. Is the task of its effective implementation still relevant in today's environment?

There is no future in a single-vector strategy. The choice of a particular set of crops in a crop rotation cannot be based solely on one factor, but only on a balanced consideration of all the factors shown in Figure 1 of the group. This should be understood by all participants. All of them, because it should lead to certain actions! On the part of farmers, given the economic logic and professional knowledge of agriculture, they do what they must do - they grow what gives results and preserves soil properties sufficiently to continue doing business. On the regulator's side, steps in economic, financial, credit, fiscal and environmental policies do not allow for the maximum benefit from the widespread use of crops in crop rotations.

Let us briefly consider the choice of crop rotation based on certain groups of factors:

1. **Ecological.**

The choice in favour of monoculture (or close to it) cultivation of agricultural crops will have the least positive impact on the water, nutrient and bioenergy regime of the soil. The existing soil type and location will also have an impact on the results of operations.

The use of the same crops on the same areas or a high frequency of their return can cause not only a sharp decline in yields but also lead to uncontrolled accumulation of chemical elements (toxins), pathogens and weed seeds in the soil. All this reduces the quality of the soil over the years.

2. **Agrotechnical.**

Given the achievements of the chemical industry and the level of technical support, today it is possible to control the level of weed infestation, effectively combat plant diseases and the spread of pests with the help of chemicals with new active ingredients or their combinations, adjusting doses, frequency and timing of treatment. Of course, such actions take place and produce the expected results: high yields at an acceptable level of spread. But there are several "buts". First, the problems with the accumulation of chemical elements, the spread of weeds and pests are not solved in this way but are only postponed indefinitely and may eventually become critical. Secondly, excessive use of chemicals in plant nutrition and protection, given unfavourable weather and climate conditions (drought, uneven precipitation, increased temperature), will no longer have the same effect in achieving even high productivity.

3. **Economic.**

Dealing with such problems without using proper crop rotations has a significant impact on the cost side of production, as elements such as mineral fertilizers and plant protection products account for up to 50% of material costs (with the cost of fuel and third-party services increasing to 55%). Therefore, additional agricultural operations will increase the cost of production without ensuring a high level of profitability. For example, over the past 5 years, the profitability of grain crops (including corn) has decreased from 42.6% to 11.8%, and that of sunflower from 78.4% to 23.5%.

In addition to the financial implications, it is easier to organize the work of an enterprise when using only a few crops, although this is mostly true for small and medium-sized farms. In large enterprises and agricultural holdings, this factor will not pose a major problem due to the well-established work of operational and logistics departments.

However, we consider diversification of production to be the most global factor, as it affects the set of crops in the crop rotation. Not only the existing activities but also the desire and ability to expand them play a role here. But this criterion is not formed in the microenvironment of the business, but depends on the situation at the macro level. If the primary basis for decision-making is the level of profitability, then at this level it is difficult to choose 7-8 or even 10 crops for most crops (most of which have rather low and unstable profitability). There are several reasons for this: volatility of prices for agricultural products on domestic and foreign markets, as well as for inputs that depend on the exchange rate; high lending rates of the banking system; uneven tax burden on business entities; lack of prospects for the development of livestock industries; stability and effectiveness of state support programs, etc. Therefore, it is worth emphasizing once again that the choice of crop rotation (if we consider this issue strategically and comprehensively) does not always depend on the commodity producer, but also on weather and climatic conditions and the overall economic situation in the country.

Therefore, when studying the issue of crop rotation, we can say the following: Ukrainian farmers still must choose. What tactics and, of course, strategy to choose depends on the skills, knowledge and, perhaps, the sense of the agricultural business management. It should be emphasized that crop rotation determines not only the agronomic strategy for increasing crop yields but also land productivity and interconnects all parts of the farming system. For the future, it is necessary to plan combinations of capital, knowledge and labor of people, proper state support and common sense (economic logic) in choosing crop rotations to obtain a positive effect for agrarian business, the state, consumers and land - in an effort to provide society with food, obtain the necessary profits for the development of the industry and preserve the potential of the land for the future.

1.2. Features of designing dynamic crop rotations

Under the conditions of intensification of agro-industrial production, the development of short-rotation crop rotations, the placement of crops in rotations in accordance with their biological requirements and rational ratios becomes especially important to ensure maximum production output and improve soil fertility.

The importance of crop rotations is hard to overestimate because they positively affect such critical factors of farming efficiency as the regulation of the nutrient regime and the increase of soil fertility; the regulation of the water regime through the accumulation and economical use of productive moisture; the prevention of soil fatigue phenomena; the regulation of the phytosanitary condition of crops, and the rational use of the bioclimatic potential of each region. To optimize conditions for plant growth, development, and high yield formation, each crop in the rotation must be provided with the most favorable predecessors. Scientifically grounded crop alternation affects the soil, changing the indicators of its chemical, physical, and biological properties. The analysis of long-term research results by scientific institutions in the Steppe region indicates that the contribution of a properly managed crop rotation accounts for 1.0–1.4 t/ha of increased winter grain yields and over 1.0 t/ha of maize. Research has proven that within a scientifically grounded crop rotation, the fertilization system, basic tillage, and pest and disease protection are reflected most efficiently.

The main reserve for achieving high and stable yields is the constant improvement of adapted technologies for specific growing zones through the implementation of scientifically grounded crop rotations and the improvement of varietal and hybrid composition of crops.

A relevant direction today is the implementation and expansion of legume crops in the structure of crop rotations, especially under the adoption of biological farming, as this improves the nitrogen balance in the soil. For example, at the present stage of farming, the emergence of new ultra-early soybean varieties makes it reasonable to evaluate their suitability for use under conditions of unstable and insufficient moisture and in short-rotation crop systems.

The main principles of building short-rotation crop rotations include the scientifically justified selection of predecessors and the optimal combination of high-yield crops while observing permissible frequency.

Dynamic mobile short-rotation crop systems require selecting the best predecessors for crops, considering their economic value and biological traits, natural environmental conditions, and cultivation technologies. The productivity of field crops largely depends on the sequence of their placement in a dynamic rotation. The highest yield can be achieved following the best predecessors (those crops that, under any agrotechnical and climatic conditions, ensure the highest yield of the subsequent crop compared to other predecessors).

In addition, all predecessors must meet the following requirements:

• timely field release;
• weed-free field;
• improvement of the phytosanitary condition of the soil;
• enhancement of the nutrient regime of the soil through fertilization with organic mass of the root system and vegetative parts of plants;
• improvement of soil structure, air and water regimes;
• absence of allelopathic effects on the seedlings of the next crop.

When designing schemes for dynamic crop rotations, it is not recommended to place cereal grains after cereals, legumes after legumes. Furthermore, special attention should be paid to observing return periods for crops to previous growing areas. The characteristics of predecessors and permissible return periods for crops in the Steppe, Forest-Steppe, and Polissya zones are presented in Tables 4 and 5.

Table 4:

Scientific recommendations on crop placement by predecessors in the Steppe and Forest-Steppe zones of Ukraine

Crops	Predecessors																	
	clean and occupied steam	by steam	winter wheat by non-steam	winter rye	barley	oats	corn for grain	peas	millet	buckwheat	sugar beet	sunflower	soybean	potatoes	corn for silage	fodder roots	annual grasses	alfalfa	sainfoin
Winter wheat	X	A	H	H	H	H	H	X	H	A	H	H	H		A	H	X	X	X
Winter rye	X	X	A	H	A	A	H	X	H	X	H	H	H		A	H	X	X	X
Barley			A	A	H	H	X		A	A	A	H	X	X	X	A			
Oats			A	A	H	H	X		A	A	A	H	X	X	X	A			
Corn for grain		X	X	X	A	A	A	A	A	X	H	H	X	A	A	A	H		
Peas			X	X	X	X	A	H	A	A	X	H	H	X	X	X		H	H
Millet		X	X	X	X	X	A		H	A	X	H	X	X	X	X			
Buckwheat		X	X	X	X	X	A		A	H	X	H	A	X	X	X			
Sugar beet		X	A	H	H	H	H		H	H	H	H	H	H	H	H			
Sunflower			X	X	X	X	A	A	A	A	H	H	A	H	A	H		H	H
Soybeans		X	X	X	X	X	A	H	A	A	Д	H	H		X	A	A	H	H
Potatoes		X	X	X	X	X	H		A	A	H	H		H	A	H	X		
Corn for silage		X	X	X	X	X	A	A	A	X	A	A	A	X	X	A			
Fodder root crops			X	A	A	H	H		H	H	H	H	H	H	A	H			
Annual grasses			X	X	X	X	X	X	X	X	X	A	A	X	X	X			
Alfalfa			X	A	X	X	A	H	A	A	H	H	H	A	A	A	X	H	H
Sainfoin			X	A	X	X	A	H	A	A	H	H	H	A	A	A	X	H	H
Rapeseed	H	X	X	X	A	A	A	A			H	H	A	A	A	H	A	H	H

Notes: x - the best precursor for placement; a - acceptable; n - unacceptable; unmarked - inappropriate

Table 5

Scientific recommendations on crop placement by predecessors in the Polissya zone of Ukraine

Predecessors	Crop										
	wheat	winter rye	barley	oats	corn	peas, vetch	lupine	flax	sugar beet	potato	sunflower
Perennial grasses (legumes)	X	X	X	X	X	H	H	X	C	X	H
Annual herbs	X	X	X	X	X	C	C	X	A	X	X
Vetch, peas	X	X	X	X	X	H	H	A	X	X	X
Lupine for green mass	X	X	X	X	X	H	H	H	C	C	C
Lupine for grain	C	C	X	X	X	H	H	X	A	X	X
Corn for silage	A	A	X	X	C	X	A	X	C	A	*X*
Corn for grain	A	A	X	X	C	X	X	X	C	A	C
Winter wheat	H	H	A	A	X	X	X	Д	X	X	X
Winter rye	H	H	A	A	X	X	X	C	X	X	X
Barley	H	C	H	C	X	X	X	C	X	A	X
Oats	C	H	C	H	X	X	X	X	A	A	X
Early potatoes	X	X	X	X	X	X	X	X	A	H	X
Late potatoes	C	C	X	X	X	X	X	X	A	H	X
Flax	X	X	X	X	X	X	X	H	C	X	X
Sugar beet	H	H	X	X	C	X	X	A	H	X	C
Sunflower	H	H	C	C	C	A	A	H	H	H	H

Notes: x - the best precursor for placement; a - acceptable, c - conditionally acceptable, n - unacceptable

The provided tables show that ideal dynamic crop rotations do not and cannot exist.

Field crops cannot always be placed after the best predecessors, as there is often a need to grow them after good, permissible, conditionally permissible, and even impermissible predecessors.

Thus, a good predecessor consistently ensures high yields of the following crop compared to other predecessors.

A permissible one guarantees stable yields of the next crop but, under extreme conditions, causes a sharp decline in its productivity.

A conditionally permissible predecessor is characterized by the fact that it significantly worsens the growing conditions for the next crop.

Finally, an impermissible predecessor creates extremely unfavorable water-physical, nutritional, and phytosanitary soil conditions for the next crop.

As for impermissible predecessors, recently, due to the increase of sunflower cultivation in Ukraine by over 5 million hectares, there is a growing need to plant a significant portion of field crops after this oilseed.

Although crop rotation principles advise avoiding sunflower as a predecessor, such fields should be designated for clean fallow (black, early, green manure, occupied, etc.).

However, with the advent of highly effective chemicals (modern herbicides, mineral fertilizers), machinery, and technologies, nearly all negative factors of impermissible predecessors are neutralized and minimized, often resulting in high yields of field crops.

Intensive technology better realizes the potential of a predecessor than conventional methods.

In other words, intensive technologies somewhat reduce the importance of predecessors because the negative effects of crop repetition are neutralized through chemical plant protection.

However, such intensification due to monoculture is extremely costly.

Therefore, producers should aim to grow major field crops after better and good predecessors not only to increase yields but also to save resources.

In general, scientists distinguish four reasons for the proper alternation of field crops:

• Chemical — the effect of correct crop alternation on nutrient conditions.

• Physical — the influence on soil structure, physical properties, and moisture.

• Biological — the effect on reducing weed infestation, pest numbers, and disease presence.

• Economic — the organizational and economic importance of crop rotation.

As for chemical reasons, they can be explained by the following theses and evidence:

- Different field crops leave varying amounts of nutrients in the soil.
- Crops remove different amounts of nitrogen, phosphorus, and potassium from the soil in different ratios. For example, cereals use more nitrogen and phosphorus, while sunflower, root, and tuber crops extract more potassium. Alternating legumes and non-legumes improves nitrogen nutrition and, in general, enhances soil nutrient conditions compared to monoculture.
- Different crops absorb nutrients from different soil layers, depending on root system depth (maize – 100 cm, winter wheat – 103, barley – 120, millet – 105, oats – 110, buckwheat – 90, rye – 113, clover – 135–150, alfalfa – 150–200, sugar beet – 246 cm). Thus, crop alternation ensures root rotation, and plants utilize nutrients from various soil horizons.
- Field crops differently absorb nutrients from poorly soluble soil compounds. For example, flax, winter wheat, and sugar beets absorb phosphorus only in readily soluble forms, while oats, potatoes, mustard, and especially buckwheat and

lupine can absorb it from poorly soluble forms, thereby improving phosphorus availability in rotations.

- In rotations, crops use nutrients from fertilizers more effectively due to improved overall nutrition conditions. Moreover, well-structured crop sequences maintain a neutral soil solution reaction.
- Field crops leave different amounts of root and post-harvest residues, which is essential for the soil organic matter balance. Introducing perennial legumes and annual grasses into rotations positively impacts humus balance.

The physical causes include the following:

1. Under the influence of the root system, different field crops have different effects on soil agrophysical parameters (structural state, density, porosity, hardness, etc.). For example, such crops as perennial grasses (alfalfa, sainfoin), winter cereals have the ability to improve the structural condition of the soil, while row crops, on the contrary, worsen it.

2. The reserves of productive moisture vary significantly under the influence of different predecessors. Individual crops are characterized by unequal water consumption in different soil layers, which is associated with different depths of root penetration. In particular, sunflower (up to 4 m), sugar beets and perennial grasses (up to 2 m), and in arid areas even up to 3.5 m, dry the soil the deepest. Other crops dry out the soil to a somewhat shallower depth (winter wheat - up to 1.8 m, peas and barley - up to 1 m, annual grasses for green fodder - up to 0.8 m). Soil moisture reserves also significantly depend on the length of the growing season.

3. Each field crop also has a certain soil protection capacity, which is determined by the presence of root and post-harvest residues, projected surface coverage, sowing methods, etc.

Among the biological causes, the most relevant are:

1. Rational crop rotation is of great importance for the control of weeds, pests and plant diseases. In particular, parasitic weeds (broomrape, bindweed) develop only on certain types of crops, so the most optimal conditions for their growth and development are in permanent crops of sunflower, tobacco, etc. Therefore, the correct alternation of these crops reduces the damage caused by weed parasites.

2. Certain weed species should be distributed mainly among certain groups of field crops. In particular, brome weed infests oats and other spring cereals, and therefore its highest concentration is usually observed in fields where spring crops are sown after spring crops.

3. Clean fallow is a reliable agronomic weed control measure with proper care during the mating period (spring-summer). Some crops (winter wheat, winter rye) have the biological ability to suppress weeds, creating optically dense crops.

4. Proper crop rotation is important in the fight against pests and diseases of field crops. For example, the sugar beet weevil lays its eggs and reproduces mainly on sugar beet crops: therefore, it is forbidden to grow them for several years in a row. If sunflower is sown without replacement, it spreads basket rot, downy mildew, sclerotinia and other diseases. Winter wheat crops are heavily damaged by the bread borer, the turtle bug, and the grain moth. And permanent legume crops are damaged by nodule weevils.

In permanent crops, fungal and bacterial diseases also affect the crops. In particular, winter wheat is heavily affected by Fusarium and brown leaf rust during 1-3 years of permanent cultivation, barley is damaged by aphids, and corn is affected by blister smut.

5. Optimal crop rotation also has a positive effect on microbiological activity in the soil. In particular, the presence of legumes in the structure of crops activates the activity of nitrogen-fixing bacteria.

1.3 Features of using short rotation crop rotations

The basis of the farming system is intensive crop cultivation technologies in crop rotation. And the main measure to stop and prevent the development of negative processes and crises in agriculture is the scientifically sound placement of crops in crop rotations.

This results in more productive use of land and fertilizers, better realization of the potential of plant varieties, reduced weed infestation, and lesser impact of pests and diseases on crops in the rotation with minimal use of chemicals. All this has a positive impact on the environment and opens up additional opportunities to increase grain production while reducing production costs.

Scientifically based crop rotation is inextricably linked to all technological measures, primarily to tillage and fertilization, seed production, and measures to combat soil erosion, weeds, diseases and pests.

Crop rotation is the basis for all technological measures. The final effect of short-rotation crop rotation depends on the composition and ratio of crops, their rotation, fertilization and tillage system.

It has been proven that the influence of the predecessor on the soil is quite diverse, and one of the important areas of this influence is the dependence on the soil water regime.

Analyzing the practice of such developed countries as Belgium, the United Kingdom, Mexico, Germany, Poland, Romania, the United States, Hungary, and Japan, we note that they recommend crop rotations with mandatory fertilization that preserve and improve soil fertility.

Sometimes simplified, particularly in the UK, grain-rich crop rotations are called alternating cereals and so-called break crops. The latter include horse beans, peas, rapeseed, potatoes, sugar beets, corn, and even oats.

The limit of saturation of crops with cereals in Germany is 65%, while in specialized crop rotations the share of cereals does not exceed 75%, and only in areas with optimal conditions it can be increased to 80%.

On average, cereals cover about 70% of the country's arable land. Repeated sowing of wheat in specialized grain crop rotations is not allowed here, even with a high culture of farming.

In Ukraine, crop rotations are specialized in three main areas: growing cereals, oilseeds and fodder crops. When considering the task of saturating crop rotations with grain crops, the literature often refers only to the share of grain in crop rotations without disclosing its species composition.

The maximum increase in crop rotation productivity is achieved at 75-100% saturation with cereals, including winter wheat, corn and other spiked crops. Under conditions of insufficient moisture, such crop rotations should include a field of black or fallow land.

Currently, there have been dramatic changes in the structure of sown areas of modern crop rotations and crop rotations practiced by domestic agricultural producers 30-40 years ago. In addition to the planned production typical of the past, the composition of crops grown was determined by the general direction of agriculture. Back then, livestock farming was an important industry.

Farms were usually the center of farms, and crop production often played the role of a fodder base. Crop rotations were organized accordingly. Today, the priorities, organization, and systems of the agricultural sector have changed. And the former 7-8-10 crop rotation structure is now becoming unprofitable and therefore rare.

Now the market, demand and price of products dictate their own rules. The reduction in the range of crops grown, the creation of smaller farms and the narrowing of their specialization make it impossible to have multi-crop rotations. Therefore, farms are increasingly switching to short rotation crop rotations.

Also, long rotation crop rotations, which were developed earlier in the country's research institutions for farms with a very large amount of arable land, a diverse set of crops and a long rotation, are now unattractive. The issue of using black manure on farms has become particularly acute, as the availability of black manure for a small set of crops can be from 25 to 50%, which is unprofitable from an economic point of view.

At the same time, violation of the basic rules of crop rotation in crop rotation leads to a deterioration in the economics of growing crops. Unfortunately, many producers act only on tactical decisions, but few think strategically. In an effort to reach the planned harvest, farmers invest huge amounts of money. And when the balance sheet is drawn up, it turns out that the profit is too low and did not justify itself.

In addition, a foothold has been prepared for even greater accumulation and development of pathogens, the spread of weeds and pests. If, indeed, crop rotation is impossible at certain points, then at least from the point of view of crop protection, it is necessary to correctly calculate the technological map, take into account weather conditions, predict in detail the development of harmful factors, and take into account all costs. This is the way to minimize risks.

Only if short-term crop rotations are properly designed can we ensure the rational use of nutrients and soil moisture, control weeds and crop pests, improve the physical and chemical properties of the soil, increase the efficiency of fertilizers and machinery, and reduce the cost of agricultural products.

The issue of developing universal crop rotations and crop rotations with short rotation, as well as the issue of optimal saturation of crops with cereals, legumes, row crops, and industrial crops, which would ensure not only high productivity and economic profit, but also the preservation and even restoration of soil fertility, is quite relevant.

Currently, one of the main factors in the biologization of agriculture, a cheap and effective non-traditional means of increasing soil fertility, is green manure (green manure) fertilizers.

Such crop rotations should be based on scientific principles, the main of which is the scientifically sound placement and rotation of crops according to the laws of crop change.

This factor is the basis for high and stable crop productivity, balanced soil fertility and phytosanitary condition of crops. The optimal rotation duration of such crop rotations should be 4 years (with variations from 3 to 5 years). This is due to the requirements for the placement of crops after their respective predecessors and compliance with the period of return of crops to the previous place of cultivation, which for most of them is 3 to 4 years.

However, there are crops (flax, lupine, sunflower, cabbage, melons) that can be returned to the previous place of cultivation in the crop rotation no earlier than in 5-8 years. Failure to comply with these standards when building crop rotations leads to the accumulation of infection in the soil and crops, the spread of pests and diseases.

Therefore, in short-rotation crop rotations, the field where such crops will be grown should be divided into two parts and these crops should be sown alternately on each of them.

Under the current conditions of competitive intensive farming, there is an increasing need to grow crops in repeated crops and to saturate crop rotations with the main economically profitable plants. Of particular importance is the knowledge of the maximum possible and cost-effective saturation of crop rotations with cereals and oilseeds, between them and corn and sunflower, taking into account organizational and climatic conditions.

Recently, the structure of sown areas has changed significantly due to an increase in corn, winter rapeseed, and spiked cereals. The area under annual and perennial grasses, sugar beets, and legumes has decreased.

Under such conditions, the issue of introducing short rotation crop rotations on farms is becoming increasingly important. In view of this, there is a need to study crop rotations with a limited set of crops that would ensure high productivity and quality and contribute to the preservation and improvement of soil fertility.

For small farms, an optimal form of land use organization should be developed based on the introduction of highly specialized short rotation crop rotations.

The construction of such crop rotations should be based on scientifically sound principles, the main of which is the placement and alternation of crops according to the laws of fruit rotation.

According to the law of fruit rotation, the crop rotation should be saturated with 50% of spiked cereals, 25% of legumes (fodder) and pulses, and 25% of row crops. This means that several crops with similar biological properties can be grown on separate fields of short rotation crop rotations, such as sugar and fodder beets, corn for grain and silage, potatoes, etc.

If the crop rotation is too simplified (up to 2-3 fields), it should include intermediate, green manure crops to reduce the phenomenon of allopathic soil fatigue, periodically introduce fallow fields or fields for fallowing, apply higher doses of organic fertilizers, and, if necessary, pesticides.

It should be borne in mind that non-compliance with these standards in crop rotation leads to the accumulation of infection in the soil and crops, the spread of pests and diseases. Such crops provide high productivity only if they are properly placed in the crop rotation, taking into account the permissible frequency of their sowing on the same field. That is why the set of crops in short rotation crop rotations is determined by the specialization of the farm, and the latter, in turn, by zonal soil and climatic conditions and market conditions.

With the introduction of short-rotation crop rotations, the importance of the crop rotation factor increases so much that it is not inferior in terms of agrotechnical efficiency, and even exceeds such measures as updating varieties and changing tillage technologies in terms of economic efficiency.

Therefore, the length of crop rotation largely depends on what crops and how many of them are to be grown. If a farm grows a large set of crops, they should be placed in multi-crop rotations. If it is planned to focus on 2 to 4 crops, then there should be short-rotation 4 to 5-field crop rotations of the fruit-shifting type.

The issue of transition from long rotation crop rotations to short rotation crop rotations should be solved in accordance with certain socio-economic, soil and environmental factors.

Before introducing a new crop rotation, it should be thoroughly and comprehensively evaluated in comparison with the previous one. Field sizes should ensure more efficient use of machinery, labor, and arable land.

Fodder crops should be located near livestock farms, which will reduce the cost of transporting feed. Attention is paid to the composition of crops that determine the output per unit area; the value of crops as predecessors; the need for mineral and organic fertilizers, tractors and agricultural machinery, warehouses, grain and potato storage facilities, etc.

They take into account the impact of crops on soil fertility, its physical and technological properties, while looking for opportunities to reduce the number of labor-intensive tillage operations. They determine the needs and specifics of using mechanical and chemical means of controlling weeds, diseases and crop pests. Such a comparative assessment of the productivity of the previous and several variants of the new crop rotation allows us to determine the crop rotation that would best meet current market conditions, ensure the reproduction of soil fertility and protect it from erosion. Crop rotations are also evaluated in terms of fodder, energy, environmental, and economic factors.

The economic importance of crops should also be taken into account. First of all, the productivity of crop rotation, where large areas are occupied by grain crops, is assessed not only in terms of the number of units, but also in terms of the yield of spring and leguminous crops per unit area. The cost of production per unit area is taken into account in the current general purchase prices for crop production. The cost of production of crops for which prices are not set is determined by calculating the content of vitamin E.

In a stationary experiment, we studied short-rotation crop rotations with different saturation with cereals, oilseeds and legumes on sod-podzolic soils in the Carpathian region (Table 6).

Table 6.

Scheme of a stationary experiment to study short-rotation crop rotations in the Carpathian region on sod-podzolic soils of the experimental field

№ variant	Crop rotation and fertilization in crop rotation					*Fertilizer applied per 1 ha of arable land, kg/ha*			
	I	II	III	IV	V	green manure, t	N	P	K
1	2	3	4	5	6	7	7	9	10
1	Fodder beans 0 – 30 – 40	Winter wheat 60 – 60 – 60				–	30	45	50
2	Winter rape 90 – 60 – 90	Winter wheat 60 – 60 – 60				–	75	60	75
3	Buckwheat 30 – 40 – 40	Winter wheat + post-harvest. 60 – 60 – 60				10	45	50	50
4	Fodder beans 0 – 30 – 40	Winter wheat 60 – 60 – 60	Winter rape 90 – 60 – 90			–	40	50	63

Continuation of tables 6

1	2	3	4	5	6	7	7	9	10
5	Spring barley 60 – 40 – 60	Winter rape 90 – 60 – 90	Winter wheat + post-harvest. 60 – 60 – 60			6,6	70	53	70
6	Spring barley + post-harvest. 60 – 40 – 60	Buckwheat 30 – 40 – 40	Winter wheat + post-harvest. 60 – 60 – 60			13,3	50	46	53
7	Fodder beans 0 – 30 – 40	Spring barley 60 – 40 – 60	Winter rape 90 – 60 – 90	Winter wheat 60 – 60 – 60		–	52	47	62
8	Spring barley 60 – 40 – 60	Winter rape 90 – 60 – 90	Winter wheat + post-harvest. 60 – 60 – 60	Buckwheat 30 – 40 – 40		5	60	50	62
9	Spring barley 60 – 40 – 60	Triticale with vetch + post-harvest. 40 – 40 – 40	Buckwheat 30 – 40 – 40	Winter wheat + post-harvest.60 – 60 – 60		10	47	45	50
10	Spring barley 60 – 40 – 60	Winter rape 90 – 60 – 90	Winter wheat + post-harvest. 60 – 60 – 60	Spring rape 60 – 50 – 60	Fodder beans 0 – 30 – 40	4	48	50	68

The formation of soil fertility indicators in short rotation crop rotations had its own peculiarities. It is closely related to the fertilization system in crop rotations. Moisture consumption in the crop rotation system significantly depended on the structure of crop rotation, the composition of the crops grown and the order of their alternation.

The highest total moisture inputs from soil and precipitation during the growing season occurred when winter wheat was grown in a two-crop rotation (320-

385 mm), compared to cereal spiked crops and legumes, where they amounted to 290-346 mm.

Instead, the simplification of crop rotations without taking into account the traditional basics and rules of crop rotation leads to a threatening spread of specialized weeds, pests and diseases, despite the growing use of chemical control agents.

First of all, winter wheat in permanent crop rotation is 1.5 to 1.8 times more susceptible to root rot, 1.5 to 2 times more susceptible to brown and yellow rust, and 1.4 to 4 times more susceptible to snow mold.

Weed infestation of winter wheat crops increases tenfold compared to crops in a crop rotation. Long-term studies have shown a significant increase in the number of winter and overwintering weeds in winter wheat crops, including common bentgrass (Apera spica-venti L.) and Sophia's bindweed (Descurainia Sophia L.). The spring crops were dominated by spring and overwintering weeds, such as small-flowered galinsoga (Galinsoga parviflora Cav), common bindweed (Amarantus retroflexus L.), common bursa (Capsella bursa pastoris L.), and field thistle (Thlaspi arvense L.) In the fourth year of uninterrupted winter wheat cultivation, its yield decreases by two to three times.

Crop yields reflect the effective soil fertility and allow to evaluate the effectiveness of the applied agricultural practices (Table 7).

Table 7.

Crop rotation productivity indicators

Crop rotation	Structure of crop rotation areas, %										*Indicators*		
	Total grains	Total oilseeds	Total legumes	out of them							grain	f. u.	Digestible protein
				winter wheat	winter rapeseed	triticale	barley	spring rapeseed	fodder beans	buckwheat			
Two-field													
1	50	–	50	50	–	–	–	–	50	–	3,19	3,855	0,463
2	50	50	–	50	50	–	–	–	–	–	3,77	5,622	0,416
3	100	–	–	50	–	–	–	–	–	50	2,98	3,265	0,270
Three- field													
4	33	33	33	33	33	–	–	–	33	–	3,18	4,620	0,431
5	66	33	–	33	33	–	33	–	–	–	3,26	4,579	0,332
6	100	–	–	33	–	–	33	–	–	33	2,76	3,075	0,239
Four-field													
7	50	25	25	25	25	–	25	–	25	–	3,17	4,401	0,391
8	75	25	–	25	25	–	25	–	–	25	3,13	4,174	0,306
9	100	–	–	25	–	25	25	–	–	25	3,27	3,663	0,271
Five-field													
10	40	40	20	20	20	–	20	20	20	–	3,14	4,625	0,390

The productivity of short-rotation crop rotations was evaluated by the yield of grain, grain and fodder units, and digestible protein per 1 ha of arable land.

On average, over the years of research, the highest grain yields of 3.19 - 3.77 t and 3.85 - 5.62 t of DM, digestible protein of 0.41 - 0.46 t/ha of arable land were obtained in crop rotations with 50% saturation with cereals and 50% with legumes with a set of crops: winter wheat, fodder beans (crop rotation 1); winter wheat, winter rape (crop rotation 2).

The productivity of short-rotation crop rotations varied depending on the share of legumes, their placement after predecessors, and fertilizer systems in the crop rotation.

Among the studied crop rotations, the highest grain yield of 3.77 t/ha of arable land was provided by a two-rotation crop rotation with a saturation of 50% grain and 50% oilseeds (winter wheat, winter rape). The conditional net profit for this crop rotation amounted to UAH 8680.2 and 94.6%.

The highest yield of 5.62 t/ha of arable land was also provided by a two-type crop rotation (variant 2) with a saturation of 50% grain and 50% oilseeds.

In terms of digestible protein, the best was the two-type crop rotation (variant 1) - 0.463 t/ha of arable land, with a saturation of 50% of cereals, 50% of legumes, conditional net profit - 6658 UAH, profitability level - 71%.

Thus, the impact of crop rotation extends to all aspects of plant life and the processes that occur in the soil, as crop rotation has no equivalent measures in terms of its effect on soil and plants. Scientifically based crop rotation is inextricably linked to all technological processes, especially tillage and fertilization, seed production, and measures to combat soil erosion, weeds, diseases, and pests, as crop rotation is the basis for all technological measures.

The environmental reasons for crop rotation are also relevant, which are formed by a complex of factors under the influence of anthropogenesis, technogenesis, and also in the case of non-compliance with the correct and complete scientifically based crop rotation in crop rotation fields. These are the reasons that determine the state and development of modern agricultural production.

The presence of crops with different biological characteristics in the crop rotation is a condition for the sustainability of agriculture. The right mix and rotation of crops in a crop rotation creates the preconditions for improving and restoring soil fertility and obtaining high yields.

In Prykarpattia, 50 years of continuous crop cultivation has had a negative impact on soil fertility, leading to increased weed infestation and the development of specialized weeds.

Triticale has the least negative impact on the soil. Winter wheat was the most resistant to no-till cultivation, with yields of 4-4.15 t/ha over the course of the long-term study.

The influence of fertilizer systems has the most significant effect on the productivity of winter rape.

Consequently, growing crops in permanent crops is impractical. Instead, scientifically based crop rotation improves the living conditions of microorganisms, increases the productivity of agrocenosis, improves product quality and the ecological state of the environment.

1.4 Efficiency of the structure of sown areas under unstable moisture conditions.

Nature has provided us with fertile soils, but significant violations of the main reasonable factors in farming have led to a catastrophic decline in their fertility. In recent years, there have been significant changes in agricultural production: in particular, there has been an excessive saturation of crop rotations with certain groups of crops, which has led to significant violations of the recommended structure of sown areas.

Recently, there has been an unjustified expansion of the area under industrial crops, such as sunflower, which causes a significant decrease in the productivity of subsequent crops in the rotation. The decline in yields of many crops is due to the lack of a properly constructed crop rotation. This phenomenon has led to a one-sided use of nutrients and significant moisture loss from the soil. At the same time, certain pests and pathogens, as well as various toxic substances, i.e., the products of plant and soil microorganisms, have accumulated in the soil. The fertilizers and pesticides used do not fully eliminate these negative effects.

Expanding agricultural production involves a number of organizational and technological measures to improve the farming system and, above all, the introduction of promising crop rotations, which are the foundation of the modern farming system.

Crop rotation is a rather important link in the entire farming system, which determines the ratio of sown areas of the main groups of crops and establishes the order of their alternation in space and time. The basis for crop rotation is a scientifically based structure that determines the rational organization of the territory, the order and sequence of arable land use. As a result of meeting its requirements, the areas allocated for sowing certain crops are specified in accordance with the specialization and concentration of agricultural production, taking into account the natural conditions and biological characteristics of each crop grown. This helps to improve the level of agricultural culture and achieve high and sustainable yields.

The structure of crop rotation areas makes it possible to effectively control weeds, diseases and pests throughout the rotation, as well as maintain all soil conditions in optimal parameters. Implementation of scientifically based crop rotations is an important agricultural measure that does not require additional material, technical and labor resources, which significantly increases the efficiency of arable land use, which contributes to higher crop yields and soil fertility, provided that the appropriate system of basic tillage and fertilization is combined with the selection of modern high-performance plant varieties and hybrids and rational measures for their effective protection.

The importance of crop rotations cannot be overestimated, as they have a positive impact on important components of agricultural efficiency. Crop rotations help to preserve soil fertility and prevent soil exhaustion, improve the phytosanitary condition of crops, regulate nutrient and water regimes (through the accumulation and economical use of productive moisture), and ensure the rational use of the soil and climatic potential of each region. All this leads to an increase in the productivity of each crop.

Crop rotation schemes should be carefully planned, taking into account the recommendations of agricultural science, and creatively applied when implementing them in production. When building crop rotations, one should take into account specific soil and climatic conditions and economic opportunities of the farm, as well as the feasibility of growing each crop that is in high demand on the market. Therefore, in modern conditions, the structure of crops in a crop rotation can vary significantly depending on the market demand for grain.

An important theoretical basis for crop rotation is fruit rotation, i.e. annual or periodic change of crops in crop rotation fields that differ in biological properties and agricultural practices. Using the principles of crop rotation allows to realize the biological productivity potential of all crops available in the crop rotation to the fullest extent possible and to ensure the preservation of soil fertility.

The State Institution Institute of Cereals of the National Academy of Agrarian Sciences of Ukraine has conducted a number of long-term studies on different types and kinds of crop rotations. As a result of the research, the permissible standards for the frequency of crops growing on the same field were established:

- for winter and spring barley, oats, buckwheat – after one year;
- for winter wheat, millet – not less than after two years;
- for corn in crop rotation or on a field temporarily removed from crop rotation – within two to three years;

• for sunflower – not less than after five, and preferably after seven or eight years.

To optimize the conditions for growth, plant development and high yields in the crop rotation, each crop must be provided with the most favorable predecessors.

Winter crops traditionally make up a significant part of the grain wedge in each growing zone. This is primarily winter wheat, 60-70% of which should be planted under the best predecessors. The best predecessors are early harvested crops, which free up the area earlier and use less productive moisture reserves.

Undoubtedly, black fallow is the best predecessor for winter wheat and must be implemented in areas of insufficient moisture. It should be borne in mind that the use of busy steam instead of black steam in the crop rotation negatively affects the yield, and in dry years causes a significant reduction in grain yield. The best non-steam predecessors for winter wheat include peas, corn for green fodder, and satisfactory ones include buckwheat, millet, and corn for silage. Today, early legumes that are harvested in time are among the priority predecessors for winter crops. Unfortunately, the precursors associated with growing crops for fodder purposes are hardly grown on most farms due to the lack of livestock.

Among winter cereals, winter barley also occupies a significant area. Most of its crops should be planted after the best predecessors, such as legumes, potatoes, and perennial legumes. About 25-30% of the crops can be planted after non-paired predecessors, among which soybeans and late harvested annual crops are the most effective. Winter barley is also planted after corn for green fodder and silage.

Given the high yields of corn and its competitive ability in the grain market, in recent years there has been a tendency to expand the area under this crop (of course, the war has made its own adjustments, and the growth of corn acreage has slowed down somewhat). The share of corn in all growing areas may increase to 40-50%. Corn should not occupy less than 20-25% of the area in the crop structure. The composition of the predecessors is also important for high corn productivity. The best predecessors for corn in crop rotations are legumes, especially soybeans, and early spring cereals and corn are satisfactory. This crop also tolerates repeated sowing for 3-4 years. In the northern Steppe, corn is most productive after winter crops and soybeans.

The composition of predecessors is also important for high productivity of corn. The best predecessors for corn in crop rotations are legumes, especially soybeans, and early spring cereals and corn are satisfactory.

A particularly important factor influencing crop productivity is the use of both early and late legumes in crop rotation, such as peas and soybeans, which, thanks to nodule bacteria, attract nitrogen from the air to feed plants grown in crop rotation. If you successfully combine these legumes in your crop rotation, you can significantly improve the nitrogen nutrition of your plants. Only effective crop rotations with the introduction of legumes and the widespread use of crop residues in combination with a rational amount of mineral fertilizers can compensate for the lack of organic fertilizers and guarantee high yields.

The share of barley in the crop rotation should not exceed 20-2 5% in the group of cereals. Barley is quite sensitive to fertilization. This crop increases yields both from fertilizers and their aftereffects. Barley responds very well to the aftereffects of fertilizers applied under the predecessor. Thus, according to the data obtained, the aftereffect of fertilizers increases the yield of this crop. It is advisable to plant barley after soybeans and corn. Spring spiked crops are unsatisfactory predecessors for it. However, in production, winter crops are often planted after early-ripening varieties and hybrids of sunflower. But with such a placement, winter crops often have poorly developed plants, primarily due to low moisture reserves and insufficient nutrients. Winter crops, even with successful overwintering and the necessary moisture reserves accumulated in the autumn-winter period, require timely implementation of all agrotechnical measures in the spring, especially the application of the necessary doses of nitrogen fertilizers, which will contribute to the rapid formation of a satisfactory vegetative mass of winter plants. However, the application of increased (according to appropriate calculations) doses of mineral fertilizers requires additional large expenditures.

In production, there are examples of successful use of grain sorghum after sunflower. Due to the low transpiration coefficient and good ability of sorghum plants to absorb nutrients from the soil, this crop forms a yield within 3.5–4.5 t/ha. Growing other grain crops after sunflower will not always give such a level of yield that will ensure significant profitability of their cultivation. With such a placement of crops, it is necessary to implement the most effective fertilization system for this part of the crop rotation.

The regulation of the concentration in crop rotations and the structure of the sown areas of grain and industrial crops allows for a significant range, which depends on the specialization of farms and allows the implementation of crop rotations with an appropriate set of crops (Table 8).

The optimal ratio between spring crops in the structure of grain crops is traditionally considered to be 1:1. However, the set and ratio of grain crops in crop rotations may vary depending on the specialization of each farm. It should be borne in mind that in large specialized farms it is advisable to introduce multi-field crop rotations with economically profitable crops. For farms where the amount of cultivated land is limited, it is better to use grain-row crop rotations with a small set of crops and a short rotation period, while increasing the share of grains to 70–80%.

The increase in crop rotation productivity to the maximum level is achieved due to 70–80% saturation with grains, including winter crops, corn and other eared crops. It is recommended to saturate crop rotations with grains by increasing the specific weight of corn and winter crops and to a lesser extent with spring eared crops.

Table 8

Recommended structure of sown areas for agricultural farms in the Steppe zone

Region	Cereals, legumes	Technical			Potatoes, vegetables, melon crops	Fodder		Black steam
		total	including			total	including, perennial herbs	
			rapeseed	sunflower				
Північно-степовий	45–80	10–30	5–10	10–12 (15–20)*	1–2	10–40	10–15	8–15
Південно-степовий	40–80	5–35	5–10	12–15 (20–25)*	1–2	10–40	8–14	10–20

** possible, but undesirable, expansion of the area of sunflower crops provided that favorable hydrothermal conditions and full compliance with the agrotechnical requirements of the cultivation technology*

Therefore, to increase the efficiency of agricultural production, all efforts of commodity producers should be directed at developing, improving, and implementing scientifically based crop rotations in combination with effective fertilization and tillage systems and modern adaptive cultivation technologies, which will increase the stability of agriculture and ensure the production of high-quality crop products.

1.5 Crop rotation as a factor in optimizing moisture and nutrient consumption

Low soil moisture content and nutrient deficiency are usually the most critical limiting factors for crop yields. Crop rotation can help optimize the use of these resources. There are three main ways to optimize water use by plants:

- moisture conservation;
- selection of an appropriate crop rotation scheme;
- implementation of effective agronomic practices.

In areas with limited moisture availability, crops typically utilize all the available water in the root zone. Therefore, key crop rotation decisions—such as whether to replant or which crop to sow—should be based on spring soil moisture content and the forecasted precipitation during the growing season.

Crop yields are more dependent on in-season rainfall than on spring soil moisture. However, spring moisture conditions can be improved through conservation measures, while seasonal rainfall cannot be controlled (except through irrigation).

Key principles of moisture conservation include:

- improving spring soil moisture by retaining snow on the field;
- preventing the loss of spring soil moisture by protecting the soil and crops from drying winds.

The most common moisture conservation practice is stubble retention, where crop residues are left on the field over winter to help trap snow. Residual stubble reduces soil moisture loss.

Undisturbed stubble 15–20 cm high can retain 12–25 mm more moisture over the winter compared to cultivated stubble. This increase of 25 mm in soil moisture can improve water uptake by plants by 3 to 11 m^3/ha, depending on the crop type and the soil-climate zone.

When using zero-tillage technology (direct seeding method), stubble remains after sowing the crop. This reduces the loss of moisture by the soil before the formation of plant cover. As shown in Fig. 5, an increase in crop yields is also observed.

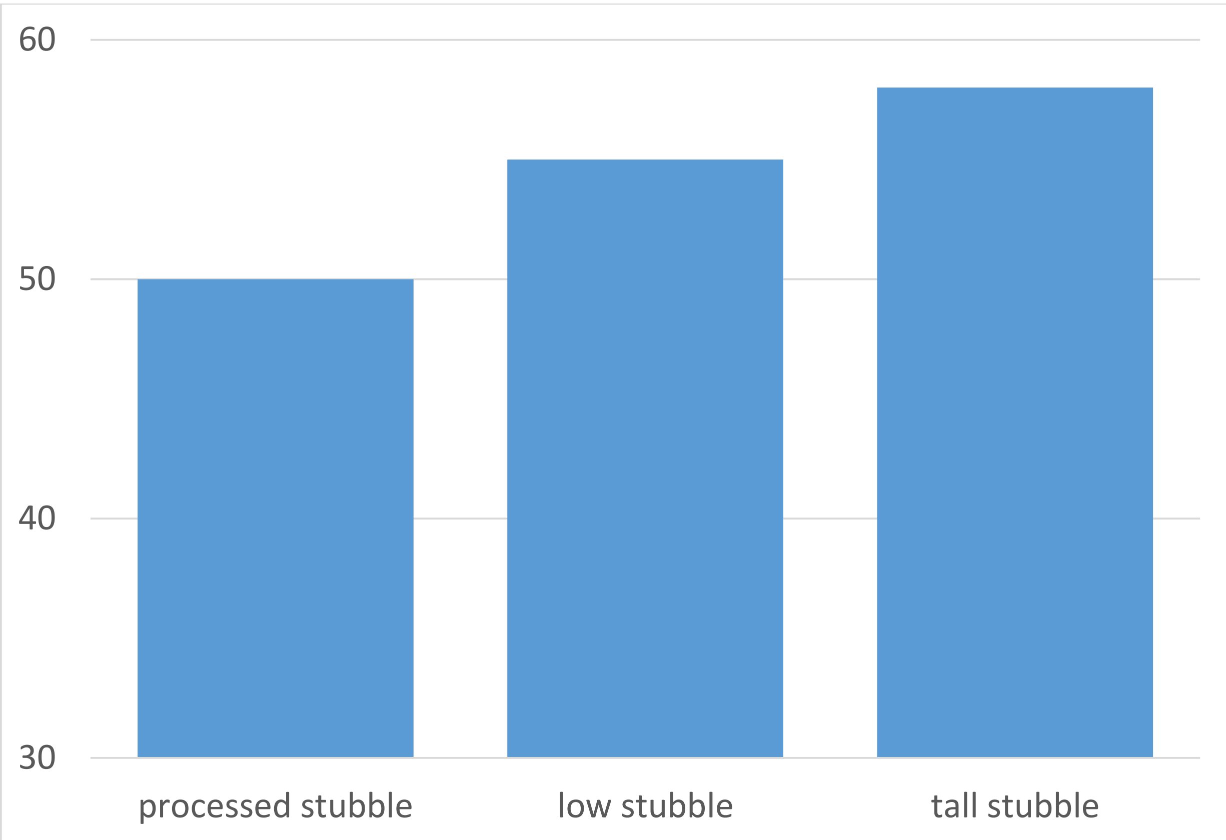

Fig. 2. The effect of stubble presence on spring wheat yield (average over four years)

The sequence of crop rotation in the crop rotation affects the accumulation and consumption of moisture, and therefore - on the yield. The thickness of the plant cover and the time of ripening are two factors that should be taken into account when planning the sequence of crops in the crop rotation.

As a rule, the root system of alfalfa, safflower, corn and sunflower is located deeper than that of barley, rapeseed, mustard, radish and wheat, in which it is, in turn, deeper than that of field peas, flax, potatoes, tomatoes and lentils (Table 9)..

Table 9

Relative depth of penetration of the root system of crops

Deep	Medium	Superficially
Alfalfa	Barley	Peas
Safflower	Rapeseed	Flax
Sunflower	Mustard	Lentils
Corn	Wheat	Potatoes
Sugar beets	Radish	Tomatoes

The depth of a plant's root system is important because water use can be optimized by alternating crops with deep and shallow root systems.

It is believed that shallow-rooted plants are better adapted when grown after deep-rooted crops, as moisture tends to replenish near the soil surface, and shallow-rooted plants do not need to expend energy searching for water deeper down where it may no longer exist.

Conversely, plants with medium or deep root systems adapt better when sown after shallow-rooted crops, as they can access residual moisture at depth, which has not been used by the previous shallow-rooted plants.

The root systems of winter wheat and rye develop at deeper levels earlier than that of spring wheat, benefiting from moisture from the previous season. The early development of fall-sown crops also means they usually flower before the peak period of summer moisture stress.

Crop rotation is also important because some crops are more sensitive to moisture deficits than others.

An experiment (results shown in Table 10) demonstrated that the yields of sunflower and safflower on fields with incorporated stubble were only slightly higher than on fields where stubble was left on the surface.

Table 10

The influence of stubble background on crop yield

Crop	Wrapping stubble into the soil	Stubble left unwrapped
Peas	28,1	24,4
Lentil	15	12,2
Mustard	17	10,7
Safflower	8,9	8,7
Sunflower	11,1	10,7
Spring wheat	27	19

The yields of peas and lentils on fields with undisturbed stubble were 81% and 86%, respectively, compared to yields on fallow fields. Wheat yielded 69%, and mustard around 63% under the same conditions.

Therefore, on a field that has undergone tillage, it is more suitable to plant wheat or mustard, while sunflower or safflower are well-suited for direct seeding into stubble.

Crop rotation also directly influences the plant's ability to utilize available moisture. Proper fertilizer application (Figure 3), along with the control of other yield-limiting factors (such as diseases, insect pests, and weeds), allows crops to use water more efficiently and better realize their yield potential.

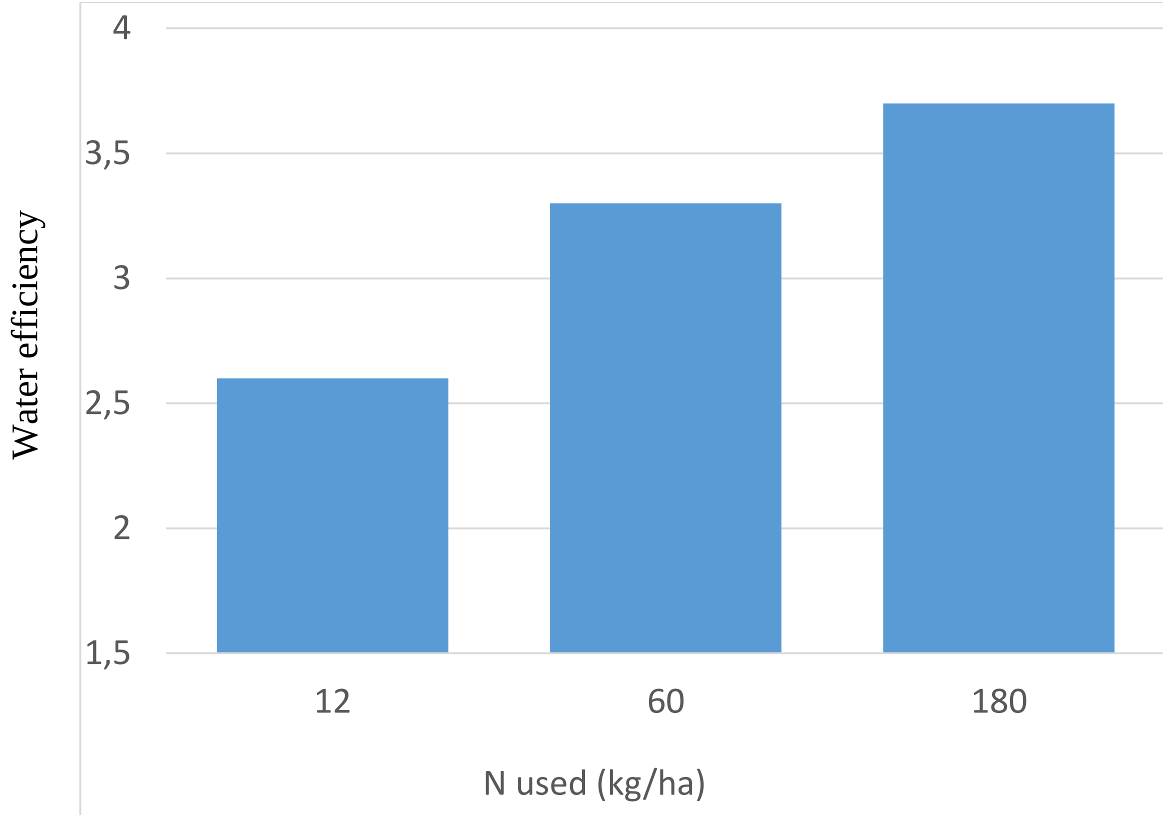

Fig. 3. The effect of nitrogen on the efficiency of moisture consumption by spring wheat

At the same time, incorrect sowing dates, inappropriate seeding depth, poor variety selection, and other factors can negatively affect yield and should also be taken into account.

In the context of crop rotation, optimizing nutrient use primarily involves selecting crops that reduce the need for fertilizer application.

Perhaps the simplest way to optimize plant nutrient use is to reduce nitrogen (N) fertilizer requirements by including legumes in the crop rotation. Legume crops can obtain 50 to 90% of their total nitrogen needs through biological nitrogen fixation, which allows for significant fertilizer cost savings during the year they are grown.

Crops planted after legumes also tend to require less nitrogen fertilizer, since nitrogen in legume residues (such as dry stems and roots) decomposes faster than that in cereal residues, allowing nitrogen to return to the soil more quickly.
However, legumes should not be planted in fields with high nitrogen content, as the plants will primarily use the readily available soil nitrogen, thereby slowing down the formation of nitrogen-fixing nodules.

Figure 4 presents research data showing that barley grown after legumes without nitrogen fertilization produced higher yields than barley grown after barley.

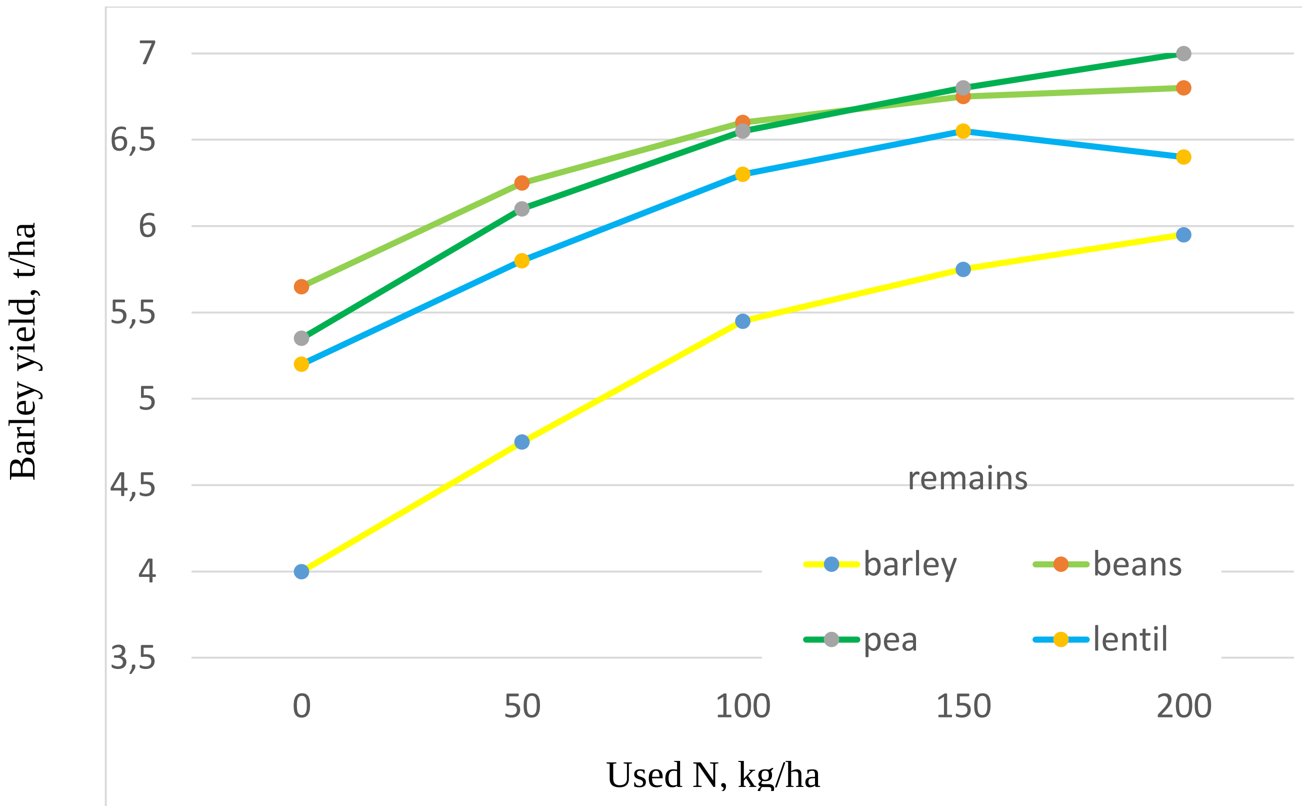

Fig. 4. Average barley yield depending on different nitrogen rates when grown after barley, beans, peas, lentil.

Also, the data in Figure 3 demonstrate that the benefit of legume as a predecessor is much greater than from the usual application of nitrogen fertilizer. In this case, the yield of barley on legume stubble exceeds the yield of barley on barley stubble up to the mark of 200 kg/ha of applied N.

Intermediate crop is another possibility for optimal use of nutrients by plants, which, however, has not received enough attention from farmers, except for organic producers. It is known that different crops have different needs for nutrients or sensitivity to their deficiency (Table 11).

Table 11

Sensitivity of crops to micronutrient deficiencies

Crop	Мікроелемент		
	Boron	Copper	Zinc
Barley	low	high	average
Rapeseed	average	average	low
Winter rye	low	low	low
Field peas	low	low	average
Flax	low	low	average
Oats	low	average	low
Winter wheat	low	high	low

One practice in the use of catch crops is to alternate those that have a high need for nutrients with those that have a low need. Such a rotation is designed to slow down the rate of increase in their deficiency. For example, the rotation of wheat - peas - oats - flax is better than the rotation of wheat - rapeseed - barley - flax, in which the copper content in the soil becomes critical.

A slightly different practice in the use of catch crops is to choose the one that can grow better with the available level of nutrients in the soil. For example, if wheat, oats or winter rye are planned to be sown, and the copper content in different fields is different, then wheat should be sown in a field with a high copper content, oats - in a field with an average level, and winter rye - in a field with a low copper content.

Returning to legumes, it is important to note that their cultivation should be avoided in fields with a high nitrogen content. In this case, legumes will primarily use the nitrogen available in the soil, thereby slowing down the formation of nodules.

At the same time, if the field where legumes are grown has a very low nitrogen content, it is recommended to apply small doses of nitrogen fertilizers (30 kg/ha) to meet the crop's needs for optimal nutrient supply at the initial stages of development.

Therefore, a well-chosen crop rotation allows you to optimize the consumption of moisture and nutrients by plants, increasing the productivity of the crop rotation as a whole.

2. CRITERIA FOR INDIVIDUAL ASSESSMENT OF MAJOR AGRICULTURAL CROPS

2.1. Agroecological assessment of the impact of weather conditions on the expected crop yield

Currently, there is no doubt that the most realistic characteristic of weather conditions that significantly affects the yield of agricultural crops is the so-called hydrothermal conditions. Hydrothermal conditions represent various types of ratios of heat and moisture resources. It is well known that the main quantitative indicators of such conditions are the hydrothermal coefficient (HTC) and the moisture coefficient (MC), which are defined as:

$$HTC = \frac{\Sigma A}{0{,}1\Sigma T^{0}C} \quad \text{and} \quad MC = \frac{RPM + \Sigma A}{0{,}1\Sigma T^{0}C} \qquad (1)$$

where: $\sum A$ – total precipitation over the period, mm;

RPM – reserves of productive moisture in the top meter of soil at the beginning of the period, mm;

$\sum T^0 C$ – the sum of the average daily air temperatures over the period, ^{0}C.

On the other hand, it is also known that each culture, at one stage or another of its development, requires "its own" individual conditions, the significance of which is optimal for that particular period. Currently, there is a fairly extensive information base regarding the assessment of the impact of weather indicators on both individual conditions or processes and crop yields. In the first group of predictive dependencies (agrometeorological conditions, the onset of periods and phases of development, the emergence and spread of diseases and pests, etc.), the use of weather indicators from the current or previous period is anticipated, with an approximation of their impact on future conditions or indicators. However, significant changes in climatic conditions over the past decades have, in one way or another, reduced the reliability of these indicators. Moreover, these forecasts often do not allow for a direct determination of the impact of specific indicators or criteria on crop yields. The second group of predictive assessments involves determining yield in absolute values (c/ha, t/ha), which at this stage is not relevant. The fact is that, as mentioned above, the widespread introduction of new high-intensity (high-yield) varieties and hybrids of agricultural crops requires an assessment of not absolute, but relative yield, that is, expressed as fractions of one. A similar impact on crop yield has been noted with cultivation technologies, or rather their intensity (see Task 1). At the same time, the yield ensured by basic resources is taken as a unit, which can be formed under optimal technological and weather conditions.

Currently, somewhat different methods for assessing weather conditions based on their impact on the relative yield of crops through special weighting factors, or productivity coefficients (α) [23, 29], have emerged. The fundamental essence of this method lies in the fact that the entire vegetation cycle of the crop is divided into periods, for each of which optimal values of indicators such as the sum of atmospheric precipitation over the period (∑A, mm) and the average daily air temperature over this period (T°C) are established. For optimal conditions, the share of influence of each period of the vegetation cycle on the crop yield is determined through the value of the impact coefficient (αT,i). Thus, under optimal conditions, the sum of the weighting factors will equal one (∑αT,i = 1.0). This means that under optimal conditions, the expected yield will match the planned or programmed yield. In the case of non-optimal conditions, the actual value of the factor for a given (i-th) period (αF,i) is less than the theoretical (optimal) value, and the sum of these indicators over the entire cycle will be less than one (∑αF,i < ∑αT,i < 1.0). At the same time, the difference between the theoretical and actual values of the sums of the indicated coefficients (∑αT,i - ∑αF,i = ∑ΔαF,i) characterizes the relative magnitude of yield losses due to non-optimal weather conditions.

It is clear that in this case, only the impact of weather conditions is being established, while all kinds of technological deviations (sparse planting, disease and pest infestation, weediness, etc.) should be taken into account with special coefficients depending on the intensity of the impact.

It should be emphasized separately that this method allows not only to assess the impact of actual weather conditions on the actual yield obtained but also to make forecasts at all stages of crop development. This is possible when, at some stage, we evaluate the part of the growing season that has passed based on actual data, and the part that is expected based on forecasted or average data.

Tables 3-6 provide optimal weather data and the structure of weight multipliers for some agricultural crops.

Table 3

Characteristics of the sunflower vegetative cycle in the Forest-Steppe and optimal air temperature values (TO, 0°C) and precipitation (AO, mm) [23]

Periods of the growing cycle	Month	Weight plural α	T_0, ^{0}C	A_0, мм
Presowing	XII-III	0,20	-5,0	180
Sowing	IV	0,05	7,6	40
Shoots – 2nd pair of true leaves	V-VI	0,19	16,0	110
Inflorescence formation – flowering	VII	0,19	19,0	80
Flowering – ripening	VIII	0,37	19,0	60
		∑=1,00		

Table 4

Characteristics of the vegetation cycle of mid-season corn in the Forest-Steppe and optimal values of air temperature (TO, 0C) and precipitation (AO, mm) [23]

Periods of the growing cycle	Month	Weight plural α	T_0, ^0C	A_0, мм
Presowing	XII-III	0,150	-1,0	170
Sowing – rooting	IV-V	0,26	11.0	100
Formation of vegetative organs	VI-VII	0,38	18,0	180
Formation of generative organs	VIII	0,14	18,0	70
Ripening	IX	0,07	12,0	10
		∑=1,00		

Table 5

Characteristics of the potato growing cycle in the Forest-Steppe and optimal values of air temperature (TO, 0C) and precipitation (AO, mm) [23]

Periods of the growing cycle	Month	Weight plural α	T_0, ^0C	A_0, мм
Planting – seedling	V	0,13	15,0	80
Seedlings - the beginning of flowering	VI	0,25	17,0	90
Flowering	VII	0,28	18,0	140
End of flowering – wilting of the tops	VIII	0,21	17,0	120
Wilting tops – harvesting	IX	0,13	12,0	65
		∑=1,00		

Table 6

Characteristics of the vegetation cycle of winter wheat in the Forest-Steppe and optimal values of air temperature (TO, 0C) and precipitation (AO, mm) [23]

Periods of the growing cycle	Month	Weight plural α	T_0, ^0C	A_0, мм
Presowing	VII-VIII	0,07	18,0	130
Sowing – rooting	IX - X	0,07	13,0	170
Shoot growth	XI	0,05	5,0	120
Winter calm	XII-II	0,29	-0,50	160
Formation of generative organs	III - V	0,36	8,0	170
Grain formation	VI	0.09	17,0	17
Achievement	VII	0.07	22,0	10
		∑=1,00		

Tables 7-12 provide data for determining the indirectly actual values of multipliers, or productivity coefficients (α), through utility or optimality coefficients for heat ($\eta(T)_i$) and precipitation ($\eta(A)_i$).

Data analysis clearly indicates that different growing periods of agricultural crops affect their yield differently.

Yes, for sunflower, the most critical period is the "flowering – ripening" period, and its impact on yield is 37% (Table 3). For corn, it is the "formation of vegetative organs" – 38% (Table 4). For potatoes, it is the "flowering" – 28% (Table 5). For winter wheat, the "winter dormancy" and "formation of generative organs" periods together account for 65% of the impact on yield (Table 6).

Table 7

Assessment of the impact of air temperature (T) on sunflower yield in the Forest-Steppe [23]

Air temperature by month, T^0C					Utility coefficient with tenths ($\eta(T)_i$)									
XII-III	IV	V-VI	VII	VIII	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
	2	11	14	14	0,75	0,76	0,77	0,78	0,79	0,80	0,81	0,82	0,83	0,84
	3	12	15	15	0,85	0,86	0,87	0,87	0,88	0,88	0,89	0,90	0,90	0,91
	4	13	16	16	0,91	0,92	0,92	0,93	0,93	0,94	0,94	0,95	0,95	0,96
	5	14	17	17	0,96	0,96	0,97	0,97	0,97	0,98	0,98	0,98	0,99	0,99
	6	15	18	18	0,99	0,99	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00
	7	16	19	19	1,00	1,00	1,00	1,00	1,00	1,00	0,99	0,99	0,99	0,98
	8	17	20	20	0,98	0,98	0,97	0,97	0,96	0,96	0,95	0,94	0,94	0,93
	9	18	21	21	0,92	0,92	0,91	0,90	0,89	0,88	0,87	0,86	0,85	0,85
	10	19	22	22	0,84	0,83	0,81	0,80	0,79	0,78	0,77	0,76	0,75	0,74
	11	20	23	23	0,73	0,71	0,70	0,69	0,68	0,67	0,65	0,64	0,63	0,52
0	12	21	24	24	0,61	0,59	0,58	0,57	0,56	0,55	0,53	0,52	0,51	0,50
2	13	22	25	25	0,49	0,48	0,46	0,45	0,44	0,43	0,42	0,41	0,40	0,39
3	14	23	26	26	0,38	0,36	0,35	0,34	0,33	0,32	0,31	0,31	0,30	0,29
Subzero temperatures														
-1					0,73	0,74	0,75	0,76	0,77	0,78	0,79	0,80	0,81	0,83
-2					0,84	0,85	0,85	0,86	0,87	0,88	0,89	0,90	0,91	0,92
-3					0,92	0,93	0,94	0,94	0,95	0,96	0,96	0,97	0,97	0,98
-4					0,98	0,98	0,99	0,99	0,99	1,00	1,00	1,00	1,00	1,00
-5					1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,99	0,99
-6					0,99	0,99	0,99	0,98	0,98	0,98	0,97	0,97	0,97	0,96
-7					0,96	0,96	0,95	0,95	0,94	0,94	0,93	0,93	0,92	0,92
-8					0,91	0,91	0,90	0,90	0,89	0,88	0,88	0,87	0,87	0,86
-9					0,85	0,84	0,84	0,83	0,81	0,80	0,79	0,78	0,77	0,76
-10					0,75	0,74	0,73	0,71	0,70	0,69	0,68	0,67	0,65	0,64
-11					0,63	0,62	0,61	0,59	0,59	0,57	0,56	0,55	0,53	0,52

Table 8

Assessment of the impact of precipitation (A) on sunflower yield in the Forest-Steppe [23]

Precipitation (A), mm	Utility coefficient for precipitation ($\eta(A)_i$)									
	0	10	20	30	40	50	60	70	80	90
Pre-sowing period (XII-III)										
0	0	0,57	0,68	0,75	0,80	0,84	0,87	0,90	0,92	0,94
100	0,95	0,97	0,98	0,99	0,99	1,00	1,00	1,00	1,00	1,00
200	1,00	0,99	0,99	0,99	0,98	0,98	0,97	0,96	0,95	0,94
300	0,93	0,92	0,91	0,90	0,89	0,87	0,86	0,85	0,83	0,81
400	0,80	0,78	0,75	0,75	0,73	0,71	0,69	0,67	0,64	0,62
500	0,59	0,58	0,55	0,53	0,50	0,47	0,44	0,42	0,38	0,36
Sowing - seedlings (IV)										
0	0	0,85	0,95	0,99	1,00	0,99	0,97	0,94	0,89	0,84
100	0,79	0,72	0,64	0,56	0,47	0,37	0,25	0,11	0	
Formation of vegetative organs (V-VI)										
0	0	0,71	0,81	0,87	0,91	0,94	0,96	0,98	0,99	1,00
100	1,00	1,00	1,00	1,00	0,99	0,98	0,98	0,97	0,95	0,94
Formation of generative organs (VII)										
0	0	0,74	0,85	0,91	0,95	0,97	0,99	1,00	1,00	1,00
100	0,99	0,98	0,97	0,95	0,93	0,92	0,89	0,87	0,84	0,81
Ripening (VIII)										
0	0	0,77	0,89	0,95	0,98	1,00	1,00	1,00	0,98	0,96
100	0,94	0,91	0,87	0,84	0,78	0,74	0,68	0,62	0,56	0,49

Table 9

Assessment of the influence of air temperature (T) on the yield of mid-season corn in the Forest-Steppe [23]

Air temperature by month, T^0C					$(\eta(T)_i)$Utility coefficient with tenths									
XII-III	IV-V	VI-VII	VIII	IX	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
	2	9	9	3	0,21	0,21	0,21	0,22	0,23	0,23	0,24	0,25	0,26	0,27
	3	10	10	4	0,28	0,29	0,30	0,31	0,31	0,32	0,33	0,34	0,35	0,36
	4	11	11	5	0,38	0,39	0,40	0,41	0,42	0,43	0,44	0,45	0,46	0,48
	5	12	12	6	0,49	0,50	0,51	0,52	0,53	0,54	0,56	0,57	0,58	0,59
	6	13	13	7	0,61	0,62	0,63	0,64	0,65	0,66	0,68	0,69	0,70	0,71
	7	14	14	8	0,73	0,74	0,75	0,76	0,77	0,78	0,79	0,80	0,82	0,83
	8	15	15	9	0,84	0,84	0,85	0,86	0,87	0,88	0,89	0,90	0,90	0,91
	9	16	16	10	0,92	0,93	0,94	0,94	0,95	0,95	0,96	0,97	0,97	0,98
	10	17	17	11	0,98	0,98	0,99	0,99	1,00	1,00	1,00	1,00	1,00	1,00
	11	18	18	12	1,00	1,00	1,00	1,00	0,99	0,99	0,99	0,98	0,97	0,97
0	12	19	19	13	0,96	0,95	0,94	0,93	0,92	0,91	0,90	0,89	0,88	0,86
1	13	20	20	14	0,85	0,84	0,83	0,81	0,79	0,78	0,76	0,75	0,73	0,71
2	14	21	21	15	0,70	0,68	0,66	0,64	0,63	0,61	0,59	0,58	0,56	0,54
3	15	22	22	16	0,53	0,51	0,50	0,48	0,46	0,44	0,43	0,41	0,40	0,38
4	16	23	23	17	0,37	0,35	0,34	0,33	0,31	0,30	0,28	0,27	0,26	0,25
Subzero temperatures														
-1					1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,99	0,99	0,98
-2					0,98	0,98	0,97	0,97	0,96	0,95	0,95	0,94	0,94	0,93
-3					0,92	0,91	0,90	0,90	0,89	0,88	0,87	0,86	0,85	0,84
-4					0,84	0,83	0,82	0,80	0,79	0,78	0,77	0,76	0,75	0,74
-5					0,73	0,71	0,70	0,69	0,68	0,67	0,66	0,64	0,63	0,62
-6					0,61	0,59	0,58	0,57	0,56	0,54	0,53	0,52	0,51	0,50
-7					0,49	0,48	0,46	0,45	0,44	0,43	0,42	0,41	0,40	0,39
-8					0,38	0,36	0,35	0,34	0,33	0,32	0,31	0,31	0,30	0,29

Table 10

Assessment of the impact of precipitation (A) on the yield of mid-season corn in the Forest-Steppe [23]

Precipitation (A), mm	Utility coefficient for precipitation ($\eta(T)_i$)									
	0	10	20	30	40	50	60	70	80	90
Pre-sowing period (XII-III)										
0	0	0,11	0,22	0,32	0,41	0,48	0,55	0,62	0,69	0,75
100	0,80	0,85	0,89	0,91	0,94	0,96	0,98	1,00	1,00	1,00
200	1,00	1,00	0,99	0,98	0,995	0,94	0,92	0,89	0,86	0,82
300	0,79	0,75	0,70	0,64	0,60	0,56	0,51	0,44	0,38	0,34
Sowing – rooting (IV - V)										
0	0	0,19	0,35	0,50	0,62	0,73	0,82	0,90	0,94	0,97
100	1,00	1,00	1,00	0,99	0,97	0,92	0,90	0,85	0,81	0,72
200	0,68	0,61	0,55	0,48	0,43	0,35	0,29	0,22	0,17	0,12
Formation of vegetative organs (VI - VII)										
0	0	0,12	0,21	0,31	0,39	0,48	0,55	0,63	0,67	0,74
100	0,80	0,83	0,88	0,91	0,94	0,95	0,97	0,98	1,00	1,00
200	1,00	0,99	0,98	0,97	0,94	0,93	0,89	0,87	0,86	0,81
Formation of generative organs (VIII)										
0	0	0,59	0,83	0,90	0,97	1,00	1,00	1,00	0,98	0,95
100	0,91	0,86	0,80	0,75	0,69	0,61	0,56	0,50	0,43	0,36
Ripening (IX)										
0	0	0,99	1,00	1,00	1,00	1,00	1,00	1,00	0,98	0,96
100	0,94	0,91	0,87	0,84	0,78	0,74	0,68	0,62	0,56	0,49

Table 11

Assessment of the influence of air temperature (T) on potato yield in the Forest-Steppe [23]

Air temperature (T,^{0}C) by periods					Utility coefficient with tenths $\eta(T)_i$				
V	VI	VII	VIII	IX	0	0,2	0,4	0,6	0,8
9	11	12	11		0,65	0,67	0,69	0,71	0,72
10	12	13	12		0,74	0,76	0,77	0,79	0,80
11	13	14	13		0,82	0,83	0,84	0,85	0,87
12	14	15	14	9	0,89	0,90	0,92	0,93	0,94
13	15	16	15	10	0,95	0,96	0,96	0,97	0,97
14	16	17	16	11	0,98	0,98	0,99	0,99	1,00
15	17	18	17	12	1,00	1,00	1,00	1,00	1,00
16	18	19	18	13	0,99	0,99	0,98	0,97	0,96
17	19	20	19	14	0,95	0,94	0,93	0,91	0,90
18	20	21	20	15	0,88	0,86	0,85	0,83	0,81
19	21	22	21	16	0,79	0,77	0,74	0,72	0,69
20	22	23	22	17	0,67	0,65	0,63	0,60	0,57
21	23	24	23	18	0,55	0,53	0,50	0,48	0,45
22	24	25	24	19	0,43	0,41	0,39	0,37	0,35

The essence of the following definitions is that for a particular crop for a given period, according to Tables 7-12, we determine the coefficients of usefulness for these resources ( ) and ( ) based on the actual values of heat and precipitation. The product of these values characterizes the actual total coefficient of usefulness for the two factors, or its compliance with optimal conditions:

$$\eta(T,A)_i = \eta(T)_i \cdot \eta(A)_i) \qquad (2)$$

Table 12

Estimation of the effect of precipitation (A) on potato yield in the Forest Steppe [23]

Precipitation (A), mm	The coefficient of usefulness for precipitation ($\eta(A)_i$)									
	0	10	20	30	40	50	60	70	80	90
May										
0	0,40	0,60	0,77	0,85	0,92	0,96	0,98	1,00	1,00	1,00
100	0,99	0,96	0,91	0,85	0,79	0,72	0,63	0,54	0,43	0,32
June										
0	0,20	0,45	0,62	0,74	0,83	0,90	0,95	0,98	0,99	1,00
100	1,00	0,99	0,97	0,93	0,87	0,79	0,69	0,55	0,36	
July										
0	0,13	0,37	0,50	0,61	0,69	0,76	0,82	0,87	0,90	0,94
100	0,96	0,98	1,00	1,00	1,00	1,00	0,99	0,98	0,96	0,94
August										
0	–	0,40	0,56	0,67	0,76	0,83	0,88	0,92	0,95	0,98
100	0,99	1,00	0,99	0,98	0,97	0,95	0,92	0,88	0,83	0,76
September										
0	–	0,75	0,88	0,96	0,99	1,00	1,00	0,98	0,95	0,90
100	0,85	0,79	0,72	0,64	0,56	0,48	0,39			

It is clear that the closer the value of this indicator is to one, the more optimal the conditions of this period are for a given crop.

The actual value of the α_F multiplier is determined as the product of the total utility coefficient and the theoretical value of the α_T multiplier:

$$\alpha_{\Phi,i} = \alpha_{T,i} \cdot \eta(T, A)_i \quad (3)$$

For example, if during the period of sunflower development “inflorescence-flowering” (July, period 4) the optimal average daily air temperature is 19.00C and the optimal amount of precipitation is 80.0 mm, then with actual data of 16.00C and

20.0 mm we have that , and from Table 3 . The total value of the coefficient of usefulness or optimality is :

$$\eta(T, A)_i = 0{,}91 \cdot 0{,}85 = 0{,}77.$$

If the normative value of the multiplier for this period is 0.19 (αT,4), its actual value will be: . This means that due to unfavorable weather conditions in July, crop losses are expected to be 4.4 % ((0.190-0.146)100 %).

Table 8, as an example, shows the calculations for assessing the compliance of actual weather conditions with the optimal ones for sunflower and their quantitative impact on crop yields, and Table 9 shows the analysis of the data obtained.

Thus, the data obtained show that the actual conditions of the sunflower growing season differed significantly from the optimal ones. At the same time, the largest deviations in the productivity coefficient were noted for almost the entire growing season with a deviation of 24.7-35.1% for individual periods (Table 13).

Table 13

Actual weather conditions of the sunflower vegetation cycle in the conditions of the Lebedyn MS for 2013-2014 and actual productivity coefficients (multipliers) [29]

Periods of the vegetation cycle	Weight plural. α_T	Months	Actual values				
			A, мм	η(A)	T^0C	η(T)	$\alpha_Ф$
Presowing	0,20	XII-III	130,0	0,98	-3,1	0,93	0,182
Sowing	0,05	IV	43,0	1,00	8,7	0,94	0,047
Shoots – 2nd pair of true leaves	0,19	V-VI	152,4	0,98	19,6	0,77	0,143
Inflorescence formation – flowering	0,19	VII	75,5	1,00	23,1	0,71	0,135
Flowering – ripening	0,37	VIII	17,9	0,80	22,2	0,81	0,240
Overall for the growing season	∑1,00						α_f =0,747

In general, the productivity coefficient was 0.747, i.e., crop losses from the unfavorable hydrothermal regime of the growing season amounted to 25.3% (0.253) (Table 14).

Table 14

General assessment of the impact of weather conditions on the productivity coefficient [29]

Periods of the growing cycle	Months	Productivity factor		
		Regulatory (α_T)	Actual (α_f)	Deviation ($\frac{Fraction}{\%}$)
Presowing	XII-III	0,20	0,182	
Sowing	IV	0,05	0,047	
Shoots – 2nd pair of true leaves	V-VI	0,19	0,143	
Inflorescence formation – flowering	VII	0,19	0,135	$\frac{0,055}{28,9}$
Flowering – ripening	VIII	0,37	0,240	$\frac{0,130}{35,1}$
Overall for the growing season		∑=1,00	0,747	$\frac{0,253}{25,3}$

So, when forecasting the yield, calculations are made on the value of the programmed yield (PY), and the formula for the yield that can be generated, or expected in this case, is as follows:

$$Y_F = PY \cdot \Sigma\alpha_F, c/ha \quad (4)$$

Thus, if at the planning stage the programmed yield was, for example, 28.0 c/ha, then in the case of the expected weather conditions, the actual expected yield will be 20.9 c/ha (28.0*0.747). In other words, in this case, 7.2 c/ha may be lost due to unfavorable hydrothermal conditions.

In the case of estimating the actual yield, for example, 26.0 c/ha, it can be argued that under optimal weather conditions, its value could be:

$$Ya = \frac{Y_F}{\Sigma \alpha_F} = \frac{26,0}{0,747} = 34,8\ c/ha$$

In this case, it seems possible to evaluate this variety by the level of its intensity in these technological conditions. Thus, if the standard yield of sunflower is 20.0 c/ha, then the actual indicator of its intensity in the conditions of the actual year will be 1.30 (26.0/20.0). At the same time, under optimal conditions, this indicator (RiC) is slightly higher and amounts to 1.74 (34.8/20.0). Of course, such a yield must be provided with basic resources and, above all, mineral nutrition.

2.2. Evaluation criteria without fertilizer application

2.2.1. Agroeconomic assessment

The essence of the definitions lies in determining the yield of each crop based on the natural fertility of the soils, that is, without the application of fertilizers, according to the main production and grain units and their value.

The basis of such calculations is the soil bonitet as the average for the crop rotation (B), the price of one bonitet point per crop yield (PB), conversion coefficients to grain units (Kg.u.), the known or accepted level of variety intensity (VI), and the purchase price (PP).

Soil bonitet (B) is a quantitative assessment of its natural fertility and is expressed in bonitet points (B ≤ 100 points). It is generally not in doubt that each field is characterized by its specific agrochemical indicators, and therefore, a specific bonitet score. However, considering that crop rotation is evaluated not in the conditions of a specific year, but over a rotation, it is advisable to introduce the average value for the crop rotation into the calculations. This value is determined under the condition:

$$B = \frac{\sum B_i \times F_i}{\sum F_i}, \text{ points} \qquad (5)$$

Currently, there are various approaches to soil bonitation based on crop yield assessment [1]:

1) overall bonitet based on crop yield;
2) agrochemical bonitet;
3) ecological-agrochemical bonitet.

In general, it can be stated that each approach to assessing soil fertility corresponds to its own value of the soil fertility point price (PB). Today, the recommended approach is the ecological-agrochemical soil fertility point [8, 10], which includes, in addition to agrochemical indicators, a number of ecological criteria (agroclimatic conditions, salinity, acidity, waterlogging, contamination with radionuclides, heavy metals, pesticide residues). At the same time, the price per point for all crops is 0.41 centner of grain equivalent per hectare, meaning that the product of the fertility score and the specified price value represents the yield of the crop in grain units:

$$UB = 0{,}41B \text{ c g.u./ha} \qquad (6)$$

To convert this value into the yield of the main product of the crop, it is necessary to divide by the conversion factor (Cf.*):*

$$\mathrm{UB} = 0{,}41\mathrm{B}/\mathrm{Cf}, \text{ c m.p./ha} \qquad (7)$$

The value of the ecological-agrochemical bonitet is determined in the "State Fertility" system, and the conversion coefficients are presented in Table 15.

Table 15

Conversion factors into grain and feed units [1, 5]

Crop	Cf
Winter wheat	1,00
Winter barley	0,90
Winter rye	0,90
Corn for grain	1,00
Spring barley	0,80
Oats	0,70
Peas	1,40
Sugar beet	0,26
Sunflower	2,00
Grain rape	2,00
Soybeans	2,00
Potatoes	1,80
Alfalfa (g/м)	0,15
Oil radish (g/м)	0,12

The given interpretation can be considered sufficient for practical calculations; however, in our opinion, a significant fact remains unaccounted for – the characteristics of the variety and technology.

The necessity of constantly increasing the efficiency of agriculture requires the intensification of both the technology of crop cultivation in general and its individual elements. The objectivity of optimizing agricultural crop cultivation is beyond doubt, as the main requirements for it, like for any other production process in market conditions, are to ensure the most economically favorable results of activity.

Currently, there are two main factors for intensifying the cultivation of agricultural crops: the variety or hybrid of the crop and the cultivation technology. The necessity of establishing the quantitative impact of these factors on crop yield is beyond doubt, as such information not only allows for setting planned yield levels and assessing the efficiency of resource use of the main factors, but also determining the economic feasibility of regulating resources in terms of yield increase costs and additional expenses.

When evaluating the quantitative impact of the variety factor on the indicators of cultivation intensification, it is necessary to determine the indicators of its intensity or yield.

Regarding the variety, it should be noted that each of the new varieties is characterized by an individual yield level determined by its genetic features. Therefore, since each new variety is more productive, it is also more intensive than the previous ones or those accepted as standard. Thus, if a new variety or hybrid has formed a higher yield than the variety accepted as standard under the same weather conditions (primarily moisture conditions) and at the same level of nutrition (natural soil fertility and fertilizer application level), this indicates that it (the new variety) is characterized by a higher coefficient of element utilization from the soil and fertilizers and a lower coefficient of total water consumption. Therefore, quantitatively, this state of affairs can be defined as the intensity level of the variety or hybrid (VI), and it can be determined as the ratio of the actual yield of the culture of this variety over the past three years to its normative level:

$$VI = \frac{Y_a}{Y_n}. \qquad (8)$$

Therefore, it shows how many times the actual yield of the crop of this variety is higher than the yield that can be determined or calculated based on normative data. In such an assessment, attention should be paid to the following conditions. First of all, it should be emphasized that the actual yield of the crop significantly depends on the weather conditions during the growing season, so from the perspective of reliability, it would be necessary to take into account the yield formed under average weather conditions, which is practically impossible. One of the options to address this could be to consider the average yield, or more precisely, the RiC value over a series of years, the average conditions of which can be considered as average conditions in general with some approximation. Moreover, the larger this series of observations (5 is better than 3), the closer the conditions are to the average, meaning the more reliable these data are. According to generally accepted conditions, a three-year series of observations can be considered sufficient for these calculations, although, one way or another, everything depends on the weather conditions of specific years and the degree of their deviation from the average data.

From the perspective of the implementation of such a resource as the level of nutrition by the crop, the normative yield is determined by existing dependencies accepted in agronomy [6. 21. 28. 32]. It is clear that such an interpretation is valid only under the condition of equality of all other technological conditions. If, during the cultivation of a new variety, additional technological operations are applied, such as the use of growth stimulants, split application of fertilizers, foliar feeding, etc., there arises a need to additionally evaluate the level of technology intensity (LiT).

The technology intensity indicator (LiT), by analogy with the previous calculation, represents the ratio of the actual yield of the crop under the new (improved) technology to the normative value for this variety, that is, based on the known value of its intensity:

$$\mathrm{LiT} = \frac{\mathrm{Y_a^{NV}}}{\mathrm{RiC}\cdot \mathrm{Y}_n} \qquad (9)$$

Therefore, the level of technology intensity indicates how many times the new (improved) technology ensures an increase in yield. It should also be noted that since actual yield depends on weather conditions, the effectiveness of any new operation also depends on these same conditions. Therefore, the technology intensity level indicator (LiT), like the previous indicator (RiC), should be determined as the average value over a series of years. At the same time, the features of each new, more intensive technology may include new forms of mineral fertilizers and methods of their application, the use of various types of micronutrients and growth stimulants, the application of calcium and sulfur, etc. Therefore, if any technological measure ensures a 20% increase in yield, it means that the intensity level of this technology (LiT) is 1.20.

Together, these two indicators can determine the overall level of agricultural technology intensity (RiA). In these calculations, it is advisable to use the concept of "varietal intensity level" (RiC), as there are some methodological inconsistencies in the quantitative assessment of technology intensity. In our case, it can be stated that if the yield of existing or baseline varieties without fertilizer application, that is, under the natural soil fertility, is determined by dependencies (2) and (3), then for new varieties it will be RiC times greater. Regarding the quantitative value of this indicator, it can be definitively stated that each new variety requires such an assessment. Calculations have shown that for the vast majority of agricultural crops, this indicator in production conditions ranges from 1.20 to 1.50 [1]. Therefore, formulas (2) and (3) can be refined as

$$У_Б = 0{,}41 \cdot RiC \cdot B, цз.о./га \qquad (6a)$$

$$У_Б = 0{,}41 \cdot RiC \cdot B/Cf, цо.п./га \qquad (7a)$$

The cost of this product is determined by the purchase price (PP), and by analogy with the previous one, the cost of the product from one hectare occupied by this crop will be determined as:

$$\mathrm{PC} = 0{,}41\mathrm{B} \cdot \mathrm{PP} \cdot \mathrm{RiC/Cf})_{\mathrm{i}}, \mathrm{UAH/ha} \qquad (10)$$

As an example, Table 16 presents such calculations for the main agricultural crops.

Table 16

Example of calculations for determining the productivity of major agricultural crops (B = 60 points)

Crop	Accepted level of variety intensity (*RiC*)	Crop yield, c/ha		Purchase price (PP), UAH/centner	Cost of production, UAH/ha
		in grain units	in the main production		
Winter wheat	1,50	36,9	36,9	180	6642
Peas	1,20	29,5	21,0	250	5250
Spring barley	1,20	29,5	32,9	160	5264
Corn for grain	1,50	36,9	36,9	110	4059
Sunflower	1,20	29,5	14,8	800	11 840

Therefore, from one hectare of crop rotation area without the application of fertilizers, one should expect 29.5 to 36.9 centners of grain units per hectare or an income of 4059 to 11,840 UAH/ha.

Thus, the simultaneous consideration of the intensity level of the variety or hybrid being grown and the intensity level of the technology or measures applied ensures a certain level of agronomy (Ra = RiC*LiT). So, if, for example, two varieties of a crop are grown under the same conditions with intensities of 1.00 (RiC1 = 1.00) and 1.50 (RiC2 = 1.50) using a technology that ensures a 20% increase in yield (LiT = 1.20), we can state that in the first case, the level of agronomy is 1.20 (1.00*1.20) and is determined by the technology, while in the second case, this indicator is 1.80 (1.50*1.20) and is determined by both the variety and the technology. This, in turn, indicates that if the resource-provided yield (normative) is, for example, 40.0 c/ha, then the planned yield in the first case is expected to be 48.0 c/ha (40.0*1.20), and in the second case, it is expected to be 72.0 c/ha (40.0*1.80).

In this task, the problem of assessing the intensity of agricultural crop varieties or hybrids and its impact on key ecological and economic indicators is considered. This is due to the large supply of new seed varieties on the market, which creates a need for expert evaluation followed by recommendations for their use in production.

Therefore, taking into account the undeniable fact that the level of technology intensity affects crop yield, a comparative assessment of varieties and hybrids based on the ratio of agronomic practice levels can be deemed appropriate.

All of the above indicates that, based on practical calculations, the assessment of varieties by their level of intensity in each farm generally characterizes the level of agronomy, since absolutely identical technological conditions do not exist. That is, the level of intensity of the variety represents the level of agronomy in its cultivation on a given farm.

2.2.2. Standard yield and calculation example

Since the impact of mineral nutrition resources on crop yield is currently the most studied and is subject to regulation, the expediency of taking as the normative yield such a value that is provided by these resources can be considered appropriate. Considering that the efficiency of the specified resource significantly depends on the conditions of natural moisture (the less moisture resource, the lower the yield), then all determinations, as indicated above, should be carried out as averages over several years.

In general, the normative or estimated crop yield by the resources of the main elements of mineral nutrition can be determined by the dependence:

$$Y_N = Y_n + \Delta Y, \text{ c/ha} \qquad (11)$$

Thus, this value represents the sum of the yields that can be generated by natural soil fertility (Yn) and the increase in yields from fertilizers (ΔY).

Given that in modern conditions the use of organic fertilizers is problematic, and the aftereffect of phosphorus and potash fertilizers is insignificant, as they are applied in unreasonably small rates, the actual rate of mineral fertilizers applied to a given crop becomes of practical importance in further calculations.

It is well known that the crop yield in the variant without fertilizers at the planning stage can be determined in different ways - in balance (through the coefficient of use of basic nutrients from the soil), through the payback of the soil bonus score by the crop yield (bonus score for crop yield, agrochemical and ecological-agrochemical soil bonus score), and actual (experimental data) crop yields under different conditions.

One of the possible and most reliable methods for assessing the increase in yield from fertilizer rates can be the method of declining yield, which is fully consistent with the nature of the impact of the resource of the main growth factors on crop yield [15, 31]. That is, the essence of this is that any subsequent value of the factor resource provides a smaller effect than the previous one. Mathematically, the nature of the influence of the fertilizer rate (X, d.m./ha) on the increase in crop yield (ΔY) is proposed to be described by the equation of a quadratic parabola:

$$\Delta У = aX^2 + вX, \quad \text{c/ha} \qquad (12)$$

In this dependence, the empirical coefficients "a" and "c" are individual for the crop, soil and climatic conditions, and the level of favorable weather conditions (favorable, average and unfavorable) [4, 5]. At the same time, the authors of this method propose to make calculations for average favorable conditions at the planning stage. Based on this dependence and given that the coefficient "a" has a negative value, the payback of fertilizers is defined as:

$$FP = в - aX, \qquad (13)$$

Thus, as the fertilizer rate increases, their profitability decreases (Fig. 1).

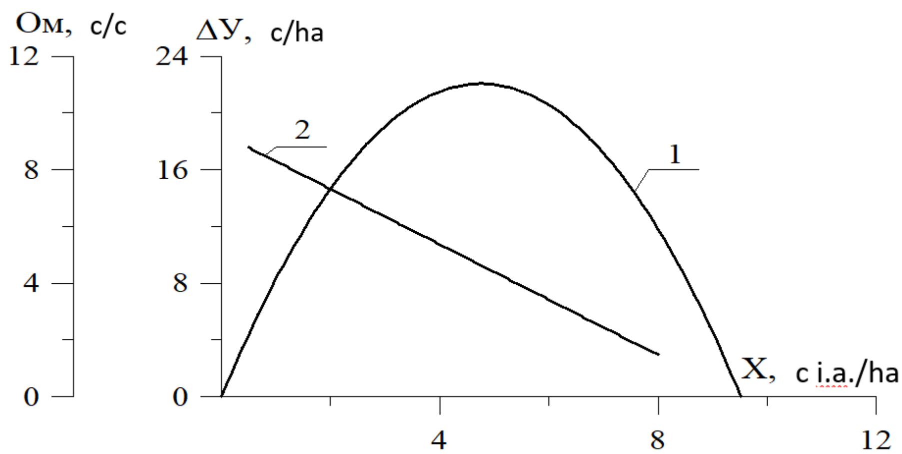

Fig. 1. The nature of the dependence of the increase in yield (1) and the payback of fertilizers (2) on their rate

The parameters of such models of crop response to fertilizers for medium favorable conditions are given in Table 17.

Table 17

Parameters of the model of yield increase (ΔU, c/ha) from mineral fertilizer rates (X, c d.r./ha) and the required ratio of elements in fertilizers) in the main soil types of Ukraine ($\Delta Y = aX^2 + вX$; $\alpha_N : \alpha_P : \alpha_K$) [4, 5]

Crop	Regression coefficients		Correlation N:P:K			Sum of the parts $\sum\alpha$
	a	*в*	α_N	α_P	α_K	
1	2	3	4	5	6	7
1. Sod-podzolic sandy and light loamy soils (Polissya)						
Winter wheat	-0,97	8,17	1,0	0,6	1,4	3,0
Spring barley	-0,75	6,88	1,0	0,6	1,4	3,0
Sunflower	-0,27	2,34	1,0	1,0	1,5	3,5
Corn for grain	-1,18	11,25	1,0	0,6	1,4	3,0
Sugar beet	-2,44	25,57	1,0	1,0	1,5	3,5
Potato	-1,56	21,84	1,0	1,0	1,5	3,5
Soybeans (peas)	-0,72	5,28	1,0	0,6	1,4	3,0
2. Sod-podzolic gleyic sandy, sandy loam and light loam soils (Polissya)						
Winter wheat	-0,65	5,51	1,0	0,6	1,4	3,0
Spring barley	-0,69	6,29	1,0	0,6	1,4	3,0
Sunflower	-0,27	2,34	1,0	1,0	1,5	3,5
Corn for grain	-0,50	4,79	1,0	0,6	1,4	3,0
Sugar beet	-2,44	25,57	1,0	1,0	1,5	3,5
Potato	-2,42	33,76	1,0	1,0	1,5	3,5
Soybeans (peas)	-0,72	5,28	1,0	0,6	1,4	3,0
3. Light gray and gray forest sandy and loamy soils (Polissya)						
Winter wheat	-1,07	9,02	1,0	0,6	1,4	3,0
Spring barley	-0,91	8,28	1,0	0,6	1,4	3,0
Sunflower	-0,27	2,34	1,0	1,0	1,5	3,5
Corn for grain	-2,43	23,13	1,0	0,6	1,4	3,0
Sugar beet	-5,00	56,48	1,0	1,0	1,5	3,5
Potato	-2,16	30,11	1,0	1,0	1,5	3,5
Soybeans (peas)	-1,34	9,81	1,0	0,6	1,4	3,0
4. Dark gray podzolized and podzolized chernozems (Forest steppe)						
Winter wheat	-1,20	10,16	1,0	0,6	1,0	2,6
Spring barley	-1,02	9,28	1,0	0,6	1,0	2,6
Sunflower	-0,43	3,71	1,0	1,0	1,2	3,2
Corn for grain	-1,21	11,56	1,0	0,6	1,0	2,6
Sugar beet	-5,26	59,28	1,0	1,0	1,2	3,2
Potato	-2,77	38,63	1,0	1,0	1,2	3,2
Soybeans (peas)	-1,39	10,16	1,0	0,6	1,0	2,6

Table continuation 17

1	2	3	4	5	6	7
5. Dark gray podzolized and podzolized gleyic chernozems (Forest-steppe)						
Winter wheat	-0,74	6,27	1,0	0,6	1,0	2,6
Spring barley	-0,86	7,88	1,0	0,6	1,0	2,6
Sunflower	-0,27	2,34	1,0	1,0	1,2	3,2
Corn for grain	-1,46	13,85	1,0	0,6	1,0	2,6
Sugar beet	-6,94	78,28	1,0	1,0	1,2	3,2
Potato	-1,72	24,07	1,0	1,0	1,2	3,2
Soybeans (peas)	-0,72	5,28	1,0	0,6	1,0	2,6
6. Typical, degraded and leached sandy and light loamy chernozems (Forest-steppe)						
Winter wheat	-0,98	8,26	1,0	0,6	1,0	2,6
Spring barley	-0,56	5,09	1,0	0,6	1,0	2,6
Sunflower	-0,45	3,92	1,0	1,0	1,2	3,2
Corn for grain	-0,97	9,27	1,0	0,6	1,0	2,6
Sugar beet	-5,92	66,79	1,0	1,0	1,2	3,2
Potato	-1,64	22,96	1,0	1,0	1,2	3,2
Soybeans (peas)	-0,72	5,28	1,0	0,6	1,0	2,6
7. Typical, degraded and leached medium and heavy loamy chernozems (Forest-steppe)						
Winter wheat	-0,82	6,94	1,0	0,6	1,0	2,6
Spring barley	-0,41	3,79	1,0	0,6	1,0	2,6
Sunflower	-0,34	2,99	1,0	1,0	1,2	3,2
Corn for grain	-1,49	14,17	1,0	0,6	1,0	2,6
Sugar beet	-4,39	49,56	1,0	1,0	1,2	3,2
Potato	-0,78	10,92	1,0	1,0	1,2	3,2
Soybeans (peas)	-0,61	4,51	1,0	0,6	1,0	2,6
8. Ordinary light and medium loamy chernozems (Steppe)						
Winter wheat	-0,84	7,12	1,0	0,6	0,6	2,2
Spring barley	-0,44	4,00	1,0	0,6	0,6	2,2
Sunflower	-0,39	3,40	1,0	1,0	0,8	2,8
Corn for grain	-0,82	7,81	1,0	0,6	0,6	2,2
Sugar beet	-3,27	36,89	1,0	1,0	0,8	2,8
Potato	-0,37	5,18	1,0	1,0	0,8	2,8
Soybeans (peas)	-0,72	5,28	1,0	0,6	0,6	2,2
9. Ordinary heavy loamy and clayey chernozems (Steppe)						
Winter wheat	-0,72	6,08	1,0	0,6	0,6	2,2
Spring barley	-0,47	4,29	1,0	0,6	0,6	2,2
Sunflower	-0,28	2,47	1,0	1,0	0,8	2,8
Corn for grain	-0,68	6,46	1,0	0,6	0,6	2,2
Sugar beet	-3,43	38,73	1,0	1,0	0,8	2,8
Potato	-0,37	5,18	1,0	1,0	0,8	2,8
Soybeans (peas)	-0,48	3,53	1,0	0,6	0,6	2,2

Table continuation 17

1	2	3	4	5	6	7
10. Southern Chernozems (Steppe)						
Winter wheat	-0,58	4,94	1,0	0,6	0,6	2,2
Spring barley	-0,39	3,59	1,0	0,6	0,6	2,2
Sunflower	-0,51	4,43	1,0	1,0	0,8	2,8
Corn for grain	-0,52	5,00	1,0	0,6	0,6	2,2
Sugar beet	-2,44	25,57	1,0	1,0	0,8	2,8
Potato	-0,37	5,18	1,0	1,0	0,8	2,8
Soybeans (peas)	-0,31	2,30	1,0	0,6	0,6	2,2
11. Dark chestnut and chestnut weakly saline (Steppe)						
Winter wheat	-0,49	4,18	1,0	0,6	0,6	2,2
Spring barley	-0,23	2,10	1,0	0,6	0,6	2,2
Sunflower	-0,28	2,47	1,0	1,0	0,8	2,8
Corn for grain	-0,47	4,48	1,0	0,6	0,6	2,2
Sugar beet	-2,44	25,57	1,0	1,0	0,8	2,8
Potato	-0,37	5,18	1,0	1,0	0,8	2,8
Soybeans (peas)	-0,19	1,41	1,0	0,6	0,6	2,2

Thus, in the case when the efficiency of mineral fertilizers is determined by the law of decreasing returns, the total standard crop yield can be expressed by the following relationship:

$$Y_N = aX^2 + bX + Y_n, c/ha \quad (14)$$

Table 18 shows the initial data for calculating the intensity level of a given (variant) crop variety using the above formulas.

The results of the calculations showed that the actual yield of winter wheat over the years ranged from 57.4 to 69.5 c/ha and depended on the rate of fertilizers, soil grade and weather conditions of the growing season and averaged 61.7 c/ha (Tables 18, 19, variant #2). The intensity index of this variety varied over the years in the range of 1.64-1.83, which, under conditions of unchanged technology over the years, characterizes fluctuations over the years and weather conditions. On average for three years, the intensity of winter wheat variety No. 2 was 1.73.

Since this variety was grown according to the technology adopted on the farm, the intensity level of the variety is individual for a given farm and numerically characterizes the level of agricultural technology on the farm when growing this variety (RiC = Ra).

Table 18

Input data for calculating variety intensity

Variant (years)	Soils (code)	Ecological-agronomic soil quality, score	Spring barley		Sunflower		Corn for grain		Winter wheat	
			X, c d.r./ha	Y_F, c/ha	X, c d.r./ha	Y_F, c/ha	X, c d.r./ha	Y_F, c/ha	X, c d.r./ha	Y_F, c/ha
1(1,2,3)	4	60	1,35	41,8	1,20	26,5	1,80	62,3	1,40	60,0
2(2,3,4)	5	62	1,35	37,6	1,35	24,8	2,20	70,0	1,60	57,4
3(3,4,5)	6	64	1,50	38,7	0,80	27,0	2,40	71,2	1,80	69,5
4(4,5,6)	7	66	1,50	37,4	1,80	27,5	2,00	71,8	1,45	58,1
5(5,6,7)	4	68	1,00	40,7	1,50	22,7	1,80	70,5	1,55	54,8
6(6,7,8)	7	70	1,00	38,9	1,65	24,8	2,20	80,8	1,60	57,3
7(7,8,9)	4	61	1,50	41,2	0,90	26,9	2,40	81,1	1,80	61,1
8(8,9,0)	5	63	1,35	36,4	1,75	26,6	2,80	75,2	1,15	52,9
9(9,0,1)	6	65	1,35	38,9	2,00	27,3	2,60	77,1	1,25	55,0
0(0,1,2)	7	67	1,50	40,5	1,90	26,3	2,40	68,2	2,10	64,0

Table 19 shows, as an example, calculations for winter wheat variety No. 2 (variant No. 2).

Table 19

An example of calculating the intensity level of winter wheat variety No. 2 (variant 2)

Year	Soil (code)	Ecological and agro-ecological soil rating, points	Yn, c/ha	Fertilizer response model	X, c d.r./ha	ΔY, c/ha	YN = Yn+ ΔY, c/ha	YF, c/ha	RiC = YF/YN
1(2)	5	62	25,4	$\Delta Y = -0{,}74X^2 + 6{,}27X$	2,20	8.1	33.5	57,4	1.71
2(3)	6	64	26,2	$\Delta Y = -0{,}98X^2 + 8{,}26X$	2,40	11.7	37.9	69,5	1.83
3(4)	7	66	27,1	$\Delta Y = -0{,}82X^2 + 6{,}94X$	2,00	8.3	35.4	58,1	1.64
Mean	**–**	**64**	**26.2**	**–**		**9.4**	**35.6**	**61,7**	**1.73**

2.2.3. Environmental assessment

It is well known that the formation of crop yields occurs through the use of such factors as light, heat, moisture, air and minerals, which are the main nutrients. The resources of all of these factors are renewable in one way or another, and only the nutrients that are part of the main product are alienated along with it. It should also be noted that the process of utilization of basic elements from the soil occurs simultaneously with the mineralization of humus, which is also a source of mineral elements necessary for plants. It is believed that about half of the nitrogen required for crop formation is supplied through humus mineralization [1]. It should also be noted that both the content of the main nutrients (N, P, K) in the soil and the humus content are the main indicators of natural soil fertility. The above suggests that the environmental assessment of crop production should take into account both the deficit of the humus balance and the deficit of basic nutrients. In addition, in some cases, especially in the current situation, it may be appropriate to evaluate both the crop and crop rotation by the amount of by-products that can be marketed, especially cereal spiked crops.

<u>Due to the deficit of humus balance</u>

It is well known that the humus balance deficit is the difference between humus losses (LH) and humus gain (GH).

Humus losses. This balance sheet item is the most complex and controversial in terms of the nature of this phenomenon [28]. In general, regulatory documents currently recommend that this indicator be determined by the following dependence [14, 15]:

$$B = G \cdot h \cdot d \quad \cdot K_1 \cdot K_2, t/ha \qquad (15)$$

where G is the humus content in the soil, %;

h - depth of the tilth layer of soil, cm;

d - soil density, t/m3;

K1 is the coefficient of humus mineralization,

K2 - relative index of biological productivity.

Of these indicators, the coefficient of humus mineralization is the most dependent on the crop, which on the chernozem soils of Polissya is [1, 26]:

- under perennial grasses - 0.0037-0.0032;
- under cereals - 0.0060-0.0052;
- under row crops - 0.0125-0.0108

Thus, for the Forest-Steppe zone (K2 = 1.065), if G = 3.60%, h = 22 cm, d = 1.25 t/m3 , the average humus losses will be

- under cereals;
- under row crops.

Thus, it can be argued that the greater the share of row crops in the crop rotation, the greater the losses of humus due to mineralization and vice versa.

Humus supply. When growing any crop, after the main product is alienated, all by-products remain in the field. According to the latest recommendations, these by-products consist of straw or leaf mass, stubble and roots. The total yield of by-products can be determined through the conversion factor to the main product (CSR) and the shares of straw (CS) and stubble and roots (SR) in this product. It should also be noted that the first half of the by-products may be marketable, as they can be used for livestock, energy, construction, etc. Thus, the by-products that remain on the field are incorporated into the soil (all or only stubble and roots) and turn into humus as a result of humification. The coefficient of plant residue humification (CRH) is individual for each zone and crop [1, 13, 21]. In addition, it is well known that to ensure optimal conditions for humification-mineralization, it is necessary to apply nitrogen fertilizers in the amount of 8-10 kg d.m./t of by-products, and most often only straw or leaf mass.

Therefore, based on the above, it can be stated that the amount of humus formed from by-products without the application of organic fertilizers per hectare of crops is defined as

$$H_F = (Y \cdot \mathrm{CSR} \cdot \mathrm{CS} \cdot \mathrm{SR}),\ \mathrm{t/ha} \qquad (16)$$

This relationship implies that when all by-products are incorporated into the soil, the KK = 1.

All the necessary initial data for further calculations are given in Table 20.

Table 20

Input data for calculations of humus formation under major crops [13, 21]

Crop	*CSR*	*CS*	*KK*	*SR*
Winter wheat	1,4	0,53	0,47	0,20
Peas	1,3	0,54	0,46	0,21
Spring barley	1,1	0,51	0,49	0,20
Corn for grain	1,5	0,58	0,42	0,20
Sunflower	2,0	0,50	0,50	0,15

Calculations for estimating the humus balance due to its deficiency are presented in Table 21.

The results show that each crop produces a rather different amount of by-products, and therefore a different amount of humus can be formed. It was found that under the accepted conditions, when straw is incorporated into the soil under such crops as winter wheat and spring barley, the amount of humus increases, i.e. there is a surplus of humus balance. Under peas, corn, and especially sunflower, a decrease in humus was recorded, with a deficit of 0.017, 0.093, and 0.757 t/ha, respectively. Under the condition of straw alienation, all of these crops show a deficit of humus balance, although of different magnitude.

Table 21

Calculation of the deficit of humus balance under the main agricultural crops

Crop	Yield, c/ha	Humus losses (LH), t/ha	By-products, t/ha			Humus gain (HG), t/ha		Humus deficiency (HD = LH - HG), t/ha	
			total	including		from all by-products products	from stubble and roots	when wrapping straw	when alienating straw
				straw	stubble and roots				
Winter wheat	36,9	0,590	5,16	2,74	2,42	1,032	0,484	–0,442	0,106
Peas	21,0	0,590	2,73	1,47	1,26	0,573	0,265	0,017	0,325
Spring barley	32,9	0,590	3,62	1,85	1,77	0,724	0,354	–0,134	0,236
Corn for grain	36,9	1,201	5,54	3,04	2,50	1,108	0,500	0,093	0,701
Sunflower	14,8	1,201	2,96	1,48	1,48	0,444	0,222	0,757	0,979

It is clear that the balance of humus in a crop rotation depends on the structure of the crops in it, i.e. not only on the crops, but also on their share in this structure. According to the logic of calculations, the higher the yield of a crop, the greater the mass of by-products, and the more humus is formed. This indicates that there is a value of crop yield that can be characterized as the minimum at which there is a zero deficit of soil balance under the crop.

This value can be determined by:

- when straw is incorporated into the soil

$$Y \geq \frac{10LH}{CSR \cdot CS_{min}}; \qquad (17)$$

- when alienating straw

$$Y \geq \frac{10LH}{CSR \cdot CS \cdot SR_{min}} \qquad (18)$$

The yield data presented in Table 22 per 1 hectare of crops can serve as a guide for a qualitative assessment of the humus balance.

Table 22

Minimum crop yields under conditions of humus balance deficit

Crop	Minimum yield, c/ha	
	when wrapping straw	when alienating straw
Winter wheat	21,1	44,8
Peas	21,6	47,0
Spring barley	26,8	54,7
Corn for grain	40,0	95,3
Sunflower	40,0	80,0

<u>For the shortage of basic nutrients</u>

The deficit of the balance of basic nutrients in the soil, by analogy with the previous one, is also the difference between the loss of elements and their supply. However, in this case, provided that no fertilizers are applied, there is no balance sheet item “receipt”, and losses are determined by the removal of these elements with the harvest of the main products, in the case of straw alienation - including it. Thus, the loss of basic nutrients due to their removal by the harvest is the deficit of their balance. The initial data for the calculations are shown in Table 23.

Based on the above, it can be argued that growing crops without fertilizers is environmentally unreasonable, since in this case there is an a priori deficit in the balance of basic nutrients. This deficit is quantified in Table 24.

Thus, the data obtained show that when growing crops without fertilizers when plowing straw into the soil, the loss of basic nutrients due to the alienation of the main product ranges from 72.4 to 170.1 kg/ha, which is the annual deficit of elements. In the case of alienation of part of the by-products (straw and leaf mass), this deficit increases significantly and ranges from 146.4 to 229.5 kg/ha. It is clear that, if necessary, such an assessment can be made for individual eluents.

Thus, the assessment of crop rotation without fertilization is the basic basis for assessing a specific crop rotation in specific soil and climatic conditions. In addition, it should be noted that when growing a crop without fertilizers, any increase in yield has a different effect both in terms of the balance of humus and the balance of the main elements. In other words, an increase in yield leads to an increase in by-products, and therefore an increase in humus supply, but at the same time, the removal of basic nutrients from the soil increases in the absence of their supply.

Table 23

Characterization of the chemical composition of the harvest of major crops [21].

Crop	Content in main products, kg/c ($C^E_{ОП}$)			Total ΣNPK, kg/c	Content in by-products, kg/c ($C^E_{ПП}$)			Removal per 1 c of straw and corresponding amount of straw, kg/c ($C^E_{ОП} + K_{СВ} \cdot K_C \cdot C^E_{ПП}$)			Total ΣNPK, kg/c
	N	P_2O_5	K_2O		N	P_2O_5	K_2O	N	P_2O_5	K_2O	
Winter wheat	2,80	0,85	0,50	4,15	0,45	0,20	0,90	2,93	1,00	1,17	5,10
Spring barley	2,10	0,85	0,55	3,50	0,50	0,20	1,00	2,38	0,96	1,11	4,45
Sunflower	2,61	1,39	0,96	4,96	1,56	0,76	5,25	4,17	2,15	6,21	12,53
Corn for grain	1,91	0,57	0,37	2,85	0,75	0,30	1,64	2,56	0,83	2,83	6,22
Soybeans (peas)*	5,80	1,04	1,26	8,10	1,20	0,31	0,63	6,64	1,26	1,70	9,60

* excluding nitrogen fixation

Table 24

Quantitative assessment of the deficit of the balance of basic nutrients in cultivation without fertilizers

Crop	Yields, c/ha	Losses (deficit) ΣNPK per 1 ha, kg/ha	
		when wrapping straw	when alienating straw
Winter wheat	36,9	153,1	188,2
Peas	21,0	170,1	201,6
Spring barley	32,9	115,2	146,4
Corn for grain	36,9	105,2	229,5
Sunflower	14,6	72,4	182,9

2.3. Crop evaluation criteria for fertilizer application

2.3.1. Expert assessment of the economic feasibility of fertilizer application

It is well known that the main indicators of economic evaluation of the efficiency of growing a crop are profit and profitability. The higher the values of these indicators, the more efficient the production, but the effect of fertilizer application is not assessed. The need for such an assessment is caused by the fact that in the case of fertilizers, there is a need for working capital (fertilizer costs), which requires an assessment of the effectiveness of the fertilizers themselves. The essence of this is to compare the cost of fertilizers with the value of the actual increase in yield from their use. It is clear that the best way to make such an assessment is to compare the results of field production experiments with the "with fertilizer" and "without fertilizer" options. However, the absence of such data in production crops requires an indirect assessment of fertilizer effectiveness [31].

In general, the level of crop yields, all other things being equal, is largely determined by the level of agricultural technology on each particular farm. Qualitatively, the level of agricultural technology is an indicator of the intensity of the technology (formation of the optimal sowing density, timeliness, quality of all technological measures, on the one hand, and their compliance with specific weather conditions, on the other) and the intensity of the variety or hybrid that was grown. It is clear that the more optimal, qualitative and adequate these measures are and the more productive (intensive) the variety is, the higher the crop yield will be, and therefore the higher the level of agricultural technology in general (Ra). As mentioned earlier, this indicator can be quantified from the ratio of the actual yield (YA) to the one that corresponds to the normative (average) return on basic resources (RR). Since in each case the actual yield depends on the crop variety and cultivation technology, the level of agricultural technology can be identified as the level of intensity of the variety in a given farm (field), which combines the intensity of the variety and the intensity of the technology.

There is no doubt that the resource that is regulated and sufficiently defined for each zone is the nutrition resource, which includes natural soil fertility and applied mineral fertilizers. In this case, the degree of nutrient resource utilization can be considered an integral indicator of agronomic conditions of crop cultivation [5, 9]. Using the payback method, this value can be determined by the following relationship:

$$Y = Yn + \Delta Y_F = Y_n + X_F \cdot P_F, c/ha \qquad (19)$$

where: Yn –the yield of a crop that can be generated due to natural soil fertility, c/ha;

ΔY_F – yield increase from mineral fertilizers, c/ha;

X_F – rate of mineral fertilizers applied for complete mineral nutrition, t/ha per year;

P_F – standardized payback of mineral fertilizers, c/c a.i.

Thus, the level of agricultural technology is quantitatively defined as:

$$Ra = \frac{YF}{YN} \qquad (20)$$

It is clear that at different stages of studying this problem, there may be different methodological approaches to determining such values as crop yields based on natural soil fertility and payback of mineral fertilizers. There is no doubt that the established values of these indicators are valid only for the technological conditions and varieties for which they were studied. For other conditions, these values should be clarified.

All of the above allows us to assert that the actual expected yield of a crop at a known level of agricultural technology on the farm can be defined as:

$$YF = Ra \cdot (Yn + X_F \cdot P_F), c/ha \quad (21)$$

Thus, the higher the level of agricultural technology on the farm, the higher the yield, all other things being equal, should be expected. On the other hand, the higher the level of agricultural technology, the lower the required rate of fertilizer for the same yield.

In the economic evaluation of growing a particular crop, the essence of the problem is that the cost of one part of the crop, called breakeven yield (YB), is used to compensate for technological costs, and the cost of the second part (the difference between the actual and breakeven yield) actually forms the profit (ΔY).

On the other hand, since the actual yield of a crop depends on the level of agricultural technology (see formula 29), and the profitable yield (ΔY) is the difference between the actual yield (Ya) and the breakeven yield (YB), it is also a function of the level of agricultural technology:

$$\Delta Y = Ya - YB = f(Ra) \quad (22)$$

Thus, the breakeven yield is determined from the condition that the value of this yield corresponds to the technological costs (TC), i.e:

$$YB \times SPP = TC, UAH/ha \quad (23)$$

where: SPP - the selling price of the product, UAH/c.

The technological costs themselves can be defined as:

$$TC = FTC + FC + HC = FTC + (X_F P_F) + HC, UAH/ha \quad (24)$$

where: *FTC* – fixed technological costs, including soil preparation for sowing, sowing and crop care, UAH/ha [5, 9];

FC – Fertilizer costs, UAH/ha;

X_F – rate of mineral fertilizers (t/ha per year);

P_F – the price of mineral fertilizers (UAH/ton), including the cost of their application;

HC – harvesting costs, UAH/ha.

Of the above costs, only harvesting costs depend on yield and can be approximated as:

$$HC = Y \times c, UAH/ha \quad (25)$$

where: c - specific productivity of the method and technique of harvesting and transportation of the crop, UAH/ton.

Based on the above, the break-even yield can be determined as follows:

$$YB = \frac{FTC + (X_F \times P_F)}{(SPP - c)}, c/ha \quad (26)$$

The above dependence shows that the break-even yield is determined by the amount of fixed costs and the ratio of prices for products and fertilizers and does not depend on the level of agricultural technology.

All of the above allows for an analytical determination of the fertilizer profitability indicator, which is based on the condition that the profitable yield in the fertilized variant should be no less than in the unfertilized variant:

$$\Delta Y_F \geq \Delta Y_{W/F} \quad (27)$$

Taking into account dependencies 30 and 34, we have from condition 35:

$$Ra_{\mathrm{KP}} \geq \frac{P_F}{P_F(SPP - \mathrm{c})} \quad (28)$$

So, all of the above shows that in order for fertilizer application to ensure an increase in profitable yields, it is necessary that the actual value of the level of agricultural technology is greater than its critical value (Ra > RaKR). Otherwise (Ra < RaKR), the yield in the “no fertilizer” variant will be lower than without fertilizers. In this case, if necessary, you can determine the critical or minimum values of the main parameters:

- or determine the minimum required yield:

$$Y_{\text{Kp}} = Ra_{\text{Kp}}(Y_n + \text{X}_F \cdot P_F), c/h\text{a} \quad (29)$$

- or set the maximum required price for mineral fertilizers:

$$P_F = Ra \cdot SPP(PF - \text{c}), UAH/c\ a.i. \quad (30)$$

- or determine the minimum allowable selling price for products:

$$SPP = \frac{PF}{Ra \cdot P_F} + \text{c}, UAH/c \quad (31)$$

All of the above cannot be a definitive assessment of the economic feasibility of fertilizer use, as such use must be profitable. That is, an increase in fertilizer doses should increase the profitability of this measure, since, by definition, fertilizer application is a measure of crop production intensification.

Thus, in the case of an increase in profitable yields from fertilizer application, and thus profit, it is necessary to assess the profitability of this measure. Thus, another limitation of fertilizer use and assessment of its economic feasibility is the condition that the profitability of the fertilizer variant is not less than that of the non-fertilizer variant: $P_F \geq P_{W/F}$, or:

$$\frac{\Delta Y_F \cdot SPP}{TC_F} 100\% \geq \frac{\Delta Y_{W/F} \cdot SPP}{TC_{W/F}} 100\% \quad (32)$$

where: and - respectively, the profitable yield of the crop with and without fertilizer;

TCF and TCW/F - respectively, technological costs with and without fertilizers.

After a number of transformations, the essence of the definitions is to compare the actual (K_E) and critical (K_E^{KP})values of the fertilizer use efficiency indicator. In this case, the actual value is determined from the condition:

$$\text{K}_\text{E} = \frac{Y_F - Y_n}{\text{X}_F \times P_F} \quad (33)$$

The critical value of this indicator is calculated by the dependence:

$$K_E^{KP} \geq \frac{P_F \cdot Y_n}{P_F \cdot FTC} \qquad (34)$$

– After that, the data is analyzed:

– if $K_E \succ K_E^{Kp}$ – fertilizer application leads to increased profitability;

– if $K_E \prec K_E^{Kp}$ – The use of fertilizers leads to a decrease in profitability.

If necessary, you can set critical values for key indicators:

– set the permissible price of mineral fertilizers:

$$P_F^P = \frac{P_F \times K_E}{Y_n} FTC, UAH/c\ a.i. \qquad (35)$$

- At the current price of fertilizers, the minimum required yield is:

$$Y_a \geq Y_n + X_F \cdot P_F \cdot K_e^{KP}, c/ha \qquad (36)$$

2.3.2. Agroeconomic assessment of the effectiveness of fertilizers themselves

It is known that the effectiveness of mineral fertilizers is determined by the characteristics of the crop and natural and climatic conditions. In addition, given that the response of a crop to a fertilizer rate is subject to the law of decreasing returns [21, 28], this effect also depends on the rate itself.

At this stage of the assessment, it may be considered appropriate to determine, first of all, the efficiency of using the first centner of mineral fertilizers, i.e., as the most efficient, when growing certain crops in the conditions of a particular soil zone.

When taking into account the effectiveness of fertilizers under the law of decreasing returns, the increase in crop yields is described by a single-vertex dome-shaped curve with the equation of a quadratic parabola, which in our case looks like this (Fig. 2):

$$\Delta Y_{\text{м}} = RiC(aX^2 + bX) \qquad (37)$$

where *RiC* – intensity level of the variety;

X – rate of mineral fertilizers, c a.i./ha;

a i *b* – empirical coefficients that are individual for the crop, zone (soil type), and conditions.

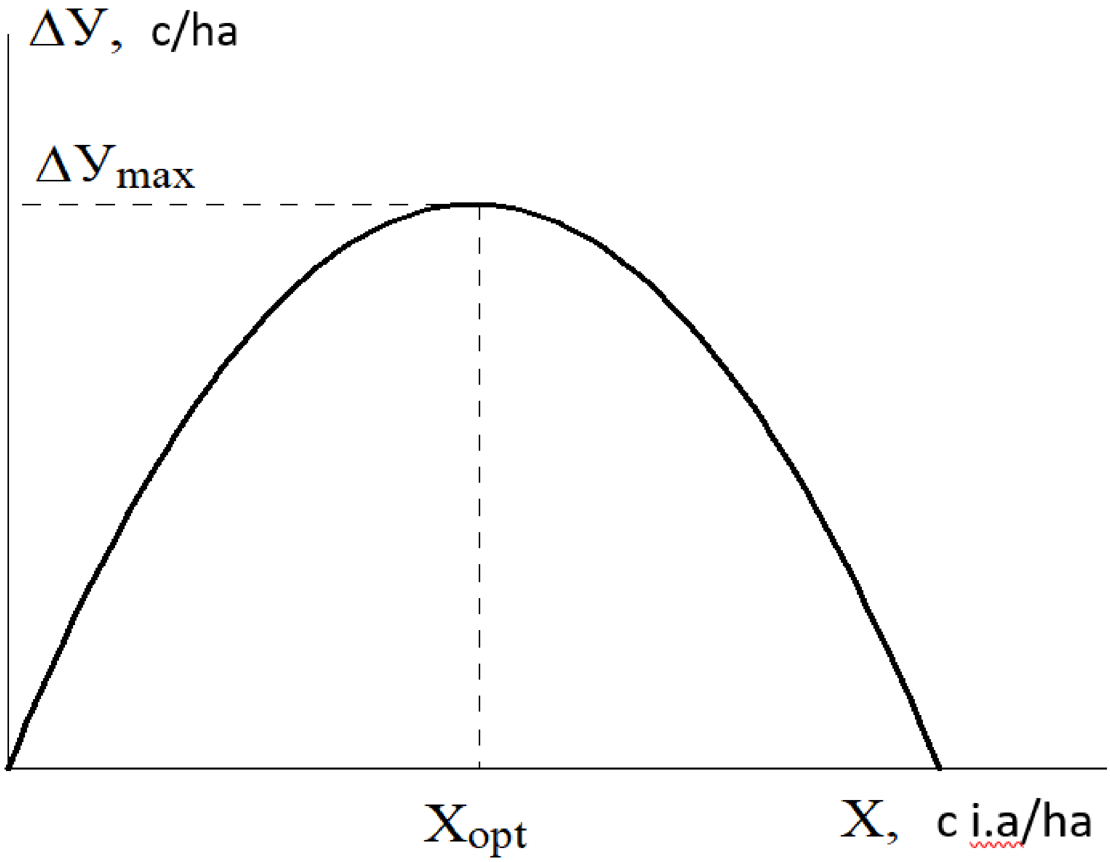

Fig. 2. The nature of the crop's response to fertilizer rate (X) in terms of yield increase (ΔY)

Table 25 shows the calculations of the efficiency of 1 centner of the active ingredient of complete mineral nutrition of individual crops and crop rotation in general on typical regraded and leached black soils [21]. The data obtained show that at current prices, the cost of additional products that can be obtained from the introduction of one (first) centner of the active ingredient of complete mineral nutrition is very different and ranges from 865.6-3328.0 UAH/ha. It should be noted that if the cost of 1 centner of the active ingredient together with the cost of application is currently about UAH 1000, then only for spring barley is the use of fertilizers unprofitable.

Table 25

Agroeconomic assessment of the efficiency of 1 c of mineral fertilizers when used for crop rotation

Crop	Accepted level of variety intensity (*RiC*)	Basic response model $\Delta Y_M = aX^2 + bX$	Yield increase, c/ha		Cost of additional production, UAH/ha
			main products	grain units	
Winter wheat	1,50	$-0,98X^2 + 8,26X$	10,92	10,92	1965,6
Peas	1,20	$-0,72X^2 + 5,28X$	5,47	7,66	1367,5
Spring barley	1,20	$-0,58X^2 + 5,09X$	5,41	4,33	865,6
Corn for grain	1,50	$-0,97X^2 + 9,27X$	12,45	12,45	1369,5
Sunflower	1,20	$-0,45X^2 + 3,92X$	4,16	8,32	3328,0

2.3.3 Agroeconomic assessment of crop efficiency when using fertilizers

By analogy with the previous definitions, Table 26 provides an individual agroeconomic assessment of the main crops when applying 1 c a.i./ha.

In this case, the yield of each crop was defined as the sum of the yields that can be formed due to natural soil fertility (Yn) and the yield increase from fertilizer application (ΔY).

Table 26

Agroeconomic assessment of main agricultural crops
with 1 c/ha of mineral fertilizers applied

Crop	Accepted level of variety intensity (*RiC*)	Crop yield, c/ha		Purchase price (PP), UAH/c	Cost of production, UAH/ha
		in grain units	in the main products		
Winter wheat	1,50	47,8	47,8	180	8604,0
Peas	1,20	37,1	26,5	250	6625,0
Spring barley	1,20	30,6	38,3	160	6128,0
Corn for grain	1,50	49,5	49,4	110	5434,0
Sunflower	1,20	38,0	19,0	800	15200,0

2.3.4. Environmental assessment of soils when applying fertilizers

<u>According to the humus balance deficit</u>

The balance of humus is calculated by analogy with the previous one, and the results of these determinations are summarized in Table 27.

It has been proven that the use of mineral fertilizers at a rate of 1 c provides not only a significant increase in yield, but also an increase in the amount of by-products, and hence the supply of humus. At the same time, under the condition of incorporating straw into the soil, a humus deficit was recorded only for sunflower.

Table 27

Calculation of humus balance deficit under major crops

when applying 1 c a.i./ha

Crop	Yield, c/ha	Loss of humus (*LH*), t/ha	By-products, t/ha			Humus supply (*HG*), t/ha		Humus deficiency (HD = LH - HG), t/ha	
			total	including		from all by-products products	from stubble and roots	when wrapping straw	when alienating straw
				straw	stubble and roots				
Winter wheat	47,8	0,590	6,69	3,55	3,14	1,338	0,628	–0,548	-0,038
Peas	26,5	0,590	3,45	1,86	1,59	0,725	0,334	–0,135	0,256
Spring barley	38,3	0,590	4,21	2,15	2,06	0,842	0,354	–0,134	0,236
Corn for grain	49,4	1,201	7,41	4,30	3,11	1,482	0,622	–0,281	0,579
Sunflower	19,0	1,201	3,80	1,90	1,90	0,570	0,285	0,631	0,916

For the shortage of basic nutrients

When establishing the deficit of basic elements in the soil in this crop rotation, the calculations were performed by analogy with the previous ones, taking into account that the supply of these elements for each crop was determined by the rate of fertilizer application, which was 100 kg of d.p./ha (Table 28).

As a result of the calculations, it was found that such a fertilizer rate (100 kg) significantly affected the deficit of basic nutrients in the soil, but it remains significant, except for sunflower.

2.4. Evaluation of crops under the condition of ensuring the absence of deficiency of basic elements in the soil

2.4.1 Conditions for lack of deficiency of basic elements in the soil

The essence of further calculations is to estimate crop rotations under the condition that the cultivation of each crop will ensure a deficit-free balance of the main nutrients. Such conditions are only possible if the amount of basic elements removed by the crop (as the main product or as the main and partially by-product) coincides with the amount of elements applied to the soil as fertilizers. It is clear that fertilizer application ensures yield growth, which in itself points to the search for a yield level at which the removal of the main elements by the crop will correspond to the rate of fertilizer application.

It is known that the yield of a crop depends on the natural fertility of the soil or its bonitas ($Yn = f(B)$) and the rate of fertilizer applied ($\Delta Y = f1(X)$):

$$Y = Yn + \Delta Y \qquad (38)$$

Table 28

Quantitative assessment of the deficit of the balance of basic nutrients at a fertilizer rate of 1 c a.i./ha

Crop	Yield, c/ha	Inflow of ΣNPK per 1 ha, kg/ha	Losses of ΣNPK per 1 ha, kg/ha		Deficit of ΣNPK for 1 ha, kg/ha	
			when wrapping straw	when alienating straw	when wrapping straw	when alienating straw
Winter wheat	47,8	100	198,4	243,8	98,4	143,8
Peas	26,5	100	214,6	254,4	114,6	154,4
Spring barley	38,3	100	134,1	170,4	34,1	70,4
Corn for grain	49,4	100	140,8	307,3	40,8	207,3
Sunflower	19,0	100	94,2	238,1	–5,8	138,1

Given the various methods currently available for determining the components of this dependence, we consider it expedient to determine the crop yield by the ecological and agrochemical soil bonanza, and the yield increase from fertilizer application by the method of decreasing returns. Taking into account the established or accepted level of variety intensity (RiC), the values of these quantities can be established by formulas (7a) and (39), respectively.

Thus, by analogy with formula (13), the type dependence can be formalized (a new method):

$$Y = aX^2 + вX + c, c/ha, \qquad (39)$$

where c - the yield that can be obtained due to natural soil fertility.

Taking into account the data in Table 16 and Table 25 for specific conditions and crops, we have:

- for winter wheat - $Y = -1{,}47X^2 + 12{,}39X + 36{,}9, c/ha$;
- for peas - $Y = -0{,}86X^2 + 6{,}34X + 21{,}0, c/ha$;
- for spring barley - $Y = -0{,}70X^2 + 6{,}11X + 32{,}9, c/ha$;
- for corn for grain - $Y = -1{,}45X^2 + 13{,}91X + 36{,}9, c/ha$;
- for sunflower - $Y = -0{,}54X^2 + 4{,}70X + 14{,}6, c/ha$.

On the other hand, it is clear that with each centner of main product some amount of NPK ($C = C^E_{OP}$) is removed. In the case of straw alienation, a slightly larger amount of elements ($C_1 = (C^E_{OP} + K_{CV} \cdot K_C \cdot C^E_{PP})$) is removed with each center of main product, as shown in Table 21. Thus, it can be argued that the amount of basic nutrients (X, c/ha) removed by the crop (Y, c/ha) is defined as:

$$X = 0{,}01У \cdot C, c/ha, \text{ or } X = 0{,}01Y \cdot C_1, c/ha. \qquad (40)$$

Звідси випливає, що кожній кількості винесення елементів відповідає конкретна урожайність:

$$Y = \frac{100X}{c}, \text{ c/ha}, \quad \text{or} \quad У_1 = \frac{100X}{C_1}, \text{c/ha}. \qquad (41)$$

Thus, ensuring the absence of shortages of basic elements is possible provided that dependencies (39) and (41) are equal, and the required fertilizer rate is determined from the model:

$$aX^2 + b_1X + c = 0, c/ha, \qquad (42)$$

where $b_1 = (b - \frac{100}{C})$, or $b_1 = (b - \frac{100}{C_1})$ (43)

The value of this rate is determined as the solution to a quadratic equation:

$$X_{1,2} = \frac{-b_1 \pm \sqrt{b_1^2 - 4ac}}{2a}, \text{ c/ha.} \qquad (44)$$

All auxiliary definitions are summarized in Table 29.

Table 29

Calculations of crop yields and the required fertilizer rate to ensure the conditions of NPK deficit-free conditions

Crop	Parameter b_1		The required fertilizer rate (*X*), c/ha		Required yield level, c/ha		Yield increase from fertilizers, c/ha	
	for straw baling	when feeling the straw	for straw baling	when feeling the straw	for straw baling	when feeling the straw	for straw baling	when feeling the straw
Winter wheat	–11,71	–7,22	2,42	3,11	58,3	61,0	21,4	24,1
Peas	–6,00	–4,08	2,56	3,11	31,6	32,4	10,6	11,4
Spring barley	–22,46	–16,36	1,40	2,62	40,0	58,9	7,1	26,0
Corn for grain	–21,18	–2,18	1,57	4,34	55,1	69,8	18,2	32,9
Sunflower	–15,46	–3,24	0,92	3,00	18,5	23,9	3,9	9,3

2.4.2 Estimation of the main crops under the condition of ensuring a deficit-free balance of the NPK

All further calculations for crop evaluation are carried out by analogy with the previous ones. Thus, according to the results of the agroeconomic assessment (Table 30), it can be argued that to ensure the given condition when straw is embedded in the soil, the required fertilizer rate is 0.92-2.56 c d.m./ha, and when it is alienated - 2.62-4.34 c d.m./ha. With such fertilizer rates, the additional yield of the main product and grain units increases significantly, as does the cost of additional products.

With regard to environmental assessment, it can be argued that by definition the balance of the main elements is not assessed, and only the balance of humus is subject to assessment. The results of the calculation of the humus balance, shown in Tables 31 and 32, convincingly show that in this variant of fertilizing crops of a given crop rotation with straw burying, a significant surplus of humus is provided after all crops except sunflower, and in the variant of straw alienation, a surplus of humus is recorded only after winter wheat and spring barley.

Table 30

Agroeconomic assessment of the main crops for the application of

of mineral fertilizers without deficit

Crop	Non-deficit fertilizer rate, tons a.i.		Growth of main product yields, c/ha		Yield increase in grain units, c/ha		Cost of additional products, UAH/ha	
	for straw baling	when feeling the straw	for straw baling	when feeling the straw	for straw baling	when feeling the straw	for straw baling	when feeling the straw
Winter wheat	2,42	3,11	21,4	24,1	21,4	24,1	3852,0	4338,0
Peas	2,56	3,11	10,6	11,4	14,8	16,0	2650,0	2850,0
Spring barley	1,40	2,62	7,1	26,0	5,7	20,8	1136,0	4160,0
Corn for grain	1,57	4,34	18,2	32,9	18,2	32,9	2002,0	3619,0
Sunflower	0,92	3,00	3,9	9,3	7,8	18,6	3120,0	7440,0

Table 31

Biomass supply and humus formation under major crops

under the condition of no NPK deficit

Crop	Required yield level, c/ha		Amount of by-products incorporated into the soil, t/ha		Humus formation, t/ha	
	for straw baling	when feeling the straw	for straw baling	when feeling the straw	for straw baling	when feeling the straw
Winter wheat	58,3	61,0	8,16	4,01	1,632	0,802
Peas	31,6	32,4	4,11	1,94	0,863	0,407
Spring barley	40,0	58,9	4,40	3,17	0,880	0,634
Corn for grain	55,1	69,8	8,26	4,40	1,652	0,880
Sunflower	18,5	23,9	3,70	2,39	0,555	0,358

Table 32

Humus balance under the main crops in the absence of NPK deficit

Crop	Humus losses (LH), t/ha	The supply of humus (*GH*), t/ha		Humus deficiency (HD = LH - HG), t/ha	
		in the variant of straw wrapping	in the variant of straw alienation	in the variant of straw wrapping	in the variant of straw alienation
Winter wheat	0,590	1,632	0,802	-1,042	-0,212
Peas	0,590	0,863	0,407	-0,273	0,183
Spring barley	0,590	0,880	0,634	-0,290	-0,044
Corn for grain	1,201	1,652	0,880	-0,451	0,321
Sunflower	1,201	0,555	0,358	0,646	0,843

2.4.3. Agroeconomic assessment of crops efficiency under conditions of lack of basic nutrients

In terms of assessing the actual deficit of basic nutrients, i.e., based on the results of growing a crop, it is necessary to compare the actual basic nutrients applied with fertilizers and those taken out with the harvest. From the point of view of crop planning, the task of assessing the lack of deficiency of basic nutrients is somewhat more complicated.

In this case, the essence of these calculations is to determine the rate of mineral fertilizers that will ensure a deficit-free balance of basic nutrients after growing any crop. In other words, the amount of nutrients applied with fertilizers should correspond to the amount of nutrients removed with the crop. From the previous calculations, it is known that the crop's response to the fertilizer rate (X, c/ha) for the base variety is defined as: $Y = aX^2 + вX + Y_n, c/ha$, and for a specific variety with a known value of the intensity level (RiC) as:

$$Y_V = RiC(aX^2 + вX + Y_n), c/ha \qquad (45)$$

On the other hand, the yield of the crop, which determines the total removal of the main elements (X), is determined from the condition:

$$Y \ = \frac{1}{\Sigma V_M} X, c/ha \qquad (46)$$

Where: ∑VM - the amount of basic nutrients taken out with the harvest of the main crop product, c a.i./c (Table 33).

It should be noted that in the case of straw alienation, significantly more elements ($\sum CB_M$) are removed from the soil than with the main product alone. This value is determined from the condition:

$$\Sigma CB_M = \Sigma B_M + (K_{CB} \cdot K_C \cdot \Sigma в_M), kg\ a.i./ha \qquad (47)$$

where: K_{CB} – yield factor of the total amount of by-products;

K_C – share of straw in by-products;

$\sum в_M$ – total content of basic nutrients in straw.

Table 33

Removal of basic nutrients with the harvest of major crops [1, 11]

Crop	K_{CB}	K_C	In main products, kg/c				In by-products, kg/c				$\sum CB_M$, кг/ц
			N	P	K	$\sum B_M$	N	P	K	$\sum B_M$	
Winter wheat	1,4	0,53	2,27	0,80	0,55	3,62	0,45	0,20	0,80	1,45	4,70
Spring barley	1,1	0,51	1,84	0,76	0,53	3,13	0,50	0,20	1,00	1,70	4,08
Corn for grain	1,5	0,58	1,53	0,59	0,42	2,64	0,75	0,30	1,64	2,69	4,88
Sunflower	2,0	0,50	2,37	1,04	0,84	4,25	1,56	0,76	5,25	7,57	11,82
Peas	1,3	0,54	3,34	0,84	1,30	5,48	1,26	0,41	0,63	2,30	7,09
Sugar beet	0,13	0,60	0,21	0,08	0,22	0,51	0,30	0,10	0,85	1,25	0,62

Thus, in essence, the problem is to find such a yield at which the amount of elements applied with fertilizers and the amount removed with the harvest would be the same, or the yield from formula 46 would be equal to the yield from formula 47. A graphic illustration of this problem is shown in Fig. 3.

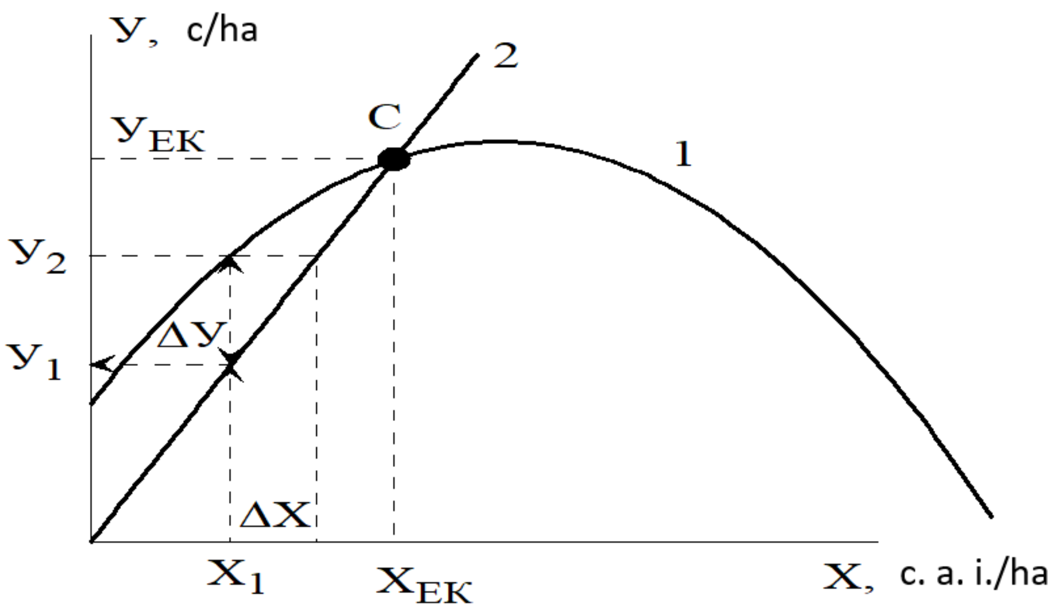

Fig. 3. Scheme for determining the equivalent rate of mineral fertilizers.

1 - model of crop yield response to mineral fertilizers (formula 1); 2 - removal of main elements by the crop yield (formula 2)

The fertilizer rate established in this way is equivalent to the amount of elements removed with the crop (ERC), and the corresponding yield is also equivalent to these conditions (YEC).

An analytical solution to the above problem is possible [1, 30], but a graph-analytical method of solution is simpler.

The fertilizer rates established in this way are deficit-free in terms of the amount of basic nutrients. To ensure the lack of deficiency of the main elements (N, P, K), the required fertilizer rate should be balanced by the ratio of these elements in the alienated products (Table 34).

Table 34

Takeaway and the ratio of the main batteries, taken out with the products

Crop	Elements			∑
	N	P	K	
1	2	3	4	5
Winter wheat				
takeaway with main products	2,27	0,80	0,55	3,62
ratio	1,0	0,36	0,25	1,61
output with main and by-products that are alienated	2,60	0,95	1,15	4,70
ratio	1,0	0,36	0,44	1,80
Spring barley				
takeaway with main products	1,84	0,76	0,53	3,13
ratio	1,0	0,41	0,29	1,70
output with main and by-products that are alienated	2,12	0,87	1,09	4,08
ratio	1,0	0,41	0,51	1,92
Corn for grain				
takeaway with main products	1,53	0,59	0,42	2,64
ratio	1,0	0,39	0,27	1,66
output with main and by-products that are alienated	2,18	0,85	1,85	4,88
ratio	1,0	0,39	0,85	2,24
Sunflower				
takeaway with main products	2,37	1,04	0,84	4,25
ratio	1,0	0,44	0,35	1,79
output with main and by-products that are alienated	3,93	1,80	6,09	11,82
ratio	1,0	0,46	1,55	3,01

Table continuation 34

1	2	3	4	5
Peas				
takeaway with main products	3,34	0,84	1,30	5,48
ratio	1,00	0,25	0,39	1,64
output with main and by-products that are alienated	4,22	1,13	1,74	7,09
ratio	1,0	0,27	0,41	1,68
Sugar beet				
takeaway with main products	0,21	0,08	0,22	0,51
ratio	1,0	0,38	1,05	2,43
output with main and by-products that are alienated	0,23	0,10	0,29	0,62
ratio	1,0	0,43	1,26	2,69

2.4.4. Agroeconomic assessment of the annual deficit of the humus balance and conditions for its non-deficit

Methodologically, the humus balance deficit is the difference between its losses and gains:

$$HD = LG - HG, t/га \quad (48)$$

Humus losses can generally be determined by the calculation method and the empirical method. In the latter case, humus losses per 1 ha can be taken from the reference literature, as shown in Table 35 [17, 25].

Table 35

Average annual values of humus mineralization under individual crops, t/ha [17, 25]

Crop	Soil type	
	Chernozem	Sod-podzolic
1	2	3
Black steam	2,00	–
Peas, vetch, soybeans	1,50	–
Winter wheat for grain	1,35	0,70
Winter wheat for green fodder	1,24	–
Annual grasses, millet, sorghum	1,10	0,70
Sugar beet	1,59	1,50
Corn for grain	1,56	–
Root crops, vegetables	1,60	1,70
Corn for silage, silos	1,47	1,25

Table continuation 35

1	2	3
Barley	1,23	0,70
Oats	1,20	0,70
Spring wheat, buckwheat, vetch-oat mixture	1,10	–
Potatoes, melons, pumpkins	1,61	1,40
Sunflower	1,39	–
Alfalfa, clover, sainfoin	0,80	0,70
Flax	–	0,90

The humus supply (HG) is defined as the result of the humification of crop and root residues left and worked into the soil (H_G^R) and applied organic fertilizers (H_G^{OF}). That is, in general, we have:

$$HG = H_G^R + H_G^{OF}, \text{ t/ha} \quad (49)$$

The mass of surface and root residues is determined through the coefficient of their total yield (CSR) as a share of the yield of the main product, and when only root residues (stubble and roots) are incorporated into the soil, i.e. when straw is alienated, it is necessary to take this condition into account through a special coefficient (CC) (Table 36).

Table 36

Coefficients of the total yield of surface and root residues of crops depending on the yield of the main product [7]

Crops	Total yield ratio of by-products, stubble and roots (CSR)	Yields of of main products, c/ha	Part of the total non-commodity weight	
			By-products (straw), CS	Stubble and roots, CC
1	2	3	4	5
Winter cereals	1,6 1,4	10 – 25 26 – 40	0,53 0,53	0,47 0,47
Barley	1,3 1,1	10 – 20 21 – 35	0,52 0,51	0,48 0,49
Oats	1,3 1,1	10 – 20 21 – 35	0,46 0,50	0,54 0,50
Millet	1,7 1,8	2 –20 21 – 30	0,47 0,55	0,53 0,45

Table continuation 36

1	2	3	4	5
Corn for grain	1,5	30 – 60	0,58	0,42
Peas	1,5 1,3	5 – 20 21 – 30	0,48 0,54	0,52 0,46
Buckwheat	1,5 1,7	5 – 15 16 – 30	0,47 0,52	0,53 0,48
Sunflower	2,0	8 – 30	0,50	0,50
Potatoes	0,40 0,14	50 – 200 200 – 400	0,45 0,50	0,55 0,50
Sugar beet	0,14 0,13	100 – 200 200 – 400	0,53 0,60	0,47 0,40
Corn for silage	-	100 – 200 200 – 350	- -	0,24 018
Annual grasses	-	100 – 140	-	0,27

Thus, taking into account the above and the dose of organic fertilizers (OF) and their humification factor (HF), it is possible to determine the supply of humus to the soil:

$$H_G = Y \cdot \mathrm{CSR} \cdot CC \cdot K_G + D_O \cdot K_{GD} \quad (50)$$

Where: KG and KGD are the humification coefficients of plant residues and organic fertilizers, respectively (Table 37).

Table 37

Humification coefficients of plant residues and manure in the soil [7].

Crop	Polissya and Forest-Steppe with humus content, %.			Steppe
	< 2,5	2,5-3,0	> 3,5	
1	2	3	4	5
Cereal grains	0,15	0,20	0,20	0,22
Corn for grain	0,15	0,15	0,20	0,20
Peas, soybeans	0,15	0,20	0,21	0,23
Cereals	0,15	0,20	0,20	0,20
Vetch	0,15	0,20	0,23	0,23
White lupine	0,15	0,20	0,20	-
Sugar and fodder beet	0,05	0,07	0,10	0,10
Sunflower	0,15	0,15	0,15	0,14

Table continuation 37

1	2	3	4	5
Rapeseed for grain	0,15	0,20	0,22	0,23
Corn for silage	0,10	0,15	0,15	0,17
Annual grasses	0,15	0,20	0,20	0,23
Winter crops for green mass	0,10	0,20	0,20	0,15
Perennial grasses for hay	0,20	0,20	0,23	0,23
Annual grasses for hay	0,10	0,20	0,22	0,22
Potatoes, vegetables	0,13	0,13	0,13	0,13
Intermediate	0,10	0,20	0,20	0,15
Litter manure	0,042	0,042	0,054	0,059
Winter crops for green fodder			0,13	
Manure (dry matter)			0,23	

The calculations are made per 1 ha of crop rotation area, with each crop taking its share (α) in tabular forms (Tables 38, 39).

Table 38

Example of calculation of annual humus losses per 1 ha of crop rotation area

Crop	Share of area under crops (α)	Humus losses, t/ha	
		Per 1 ha, LH (Table 5)	On the area α
1. Soybeans	0,20	1,50	0,300
2. Winter wheat	0,20	1,35	0,270
3. Corn for grain	0,20	1,56	0,312
4. Spring barley	0,20	1,23	0,246
5. Oats	0,20	1,20	0,240
Total for 1 hectare of crop rotation area			∑1,368 t/ha

Table 39

An example of calculating humus supply per 1 ha of crop rotation area

Crops	Y, t/ha	Y for area (α), t	YPP for area (α), t		Humus supply, t	
			Total	Roots and stubble	Total	With roots and stubble
1. Soybeans	2,6	0,52	0,676	0,311	0,141	0,065
2. Winter wheat	6,4	1,28	1,792	0,842	0,358	0,168
3. Corn for grain	7,3	1,46	2,190	0,919	0,438	0,184
4. Spring barley	3,2	0,64	0,704	0,345	0,171	0,069
5. Oats	3,0	0,60	0,660	0,330	0,132	0,066
Total for 1 hectare of crop rotation area					∑ 1,240	∑ 0,552

The yield of the main product per share of a hectare of crop rotation (α) is defined as:

$$Y_{PP}^{\alpha} = Y_{OP}^{\alpha} \cdot \mathrm{a}, t \qquad (51)$$

The yield of all by-products from an area α is defined as the product of the yield of the main product (YP) and the total yield coefficient (TSC) (see Table 34):

$$Y_{PP}^{\alpha} = Y_{OP}^{\alpha} \cdot \mathrm{CSR}, t \qquad (52)$$

Yields of stubble and root by-products are determined as a proportion of their total value (see Table 34):

$$\text{У}_{PP(\text{К})}^{\alpha} = \text{У}_{PP}^{\alpha} \cdot \text{К}_{\text{К}}, t \qquad (53)$$

The supply (formation) of humus is the product of by-products or a part of them and the humification coefficient (HC) (formula 51):

So, based on formula 49, we have that if all by-products are incorporated into the soil, the deficit of the humus balance (LH) on one hectare of crop rotation area will be:

LH = 1,368 – 1,240 = 0,128 t/ha

In the case of alienation of all straw as part of the by-products, i.e. when only stubble and roots are incorporated into the soil, the deficit will be:

LH = 1,368 – 0,552 = 0,816 t/ha

Thus, it can be argued that even if all by-products are incorporated into the soil, the resulting annual deficit in the humus balance must be compensated for by additional organic fertilization in the form of manure or green manure, and quantitative calculations are made for the entire crop rotation area.

There is no doubt that the resulting humus deficit must be compensated for in some way. One of the options for such compensation can be cattle bedding manure, which has a humification coefficient (HCC) of 0.054 (see Table 37). In this case, the required rate (dose) of organic fertilizers is defined as:

$$D_{OF} = \frac{HL}{K_{GD}}, t/ha \qquad (54)$$

In our case, we have that when all by-products are incorporated into the soil, the required dose of manure is about 2.4 t/ha of crop rotation area

(0,128 /0,054). In case of alienation of these products, it is 15.1 t/ha of crop rotation area (0.816/0.054). That is, if the crop rotation area is 1000 hectares, then the annual need for organic fertilizers is 2400 tons, and otherwise - 15100 tons. Thus, given that the annual yield of bedding manure from 1 head of cattle is about 10 tons, then 240 heads of cattle are needed per 1000 hectares of arable land in the first case, and 1510 in the other, which is unrealistic under current conditions.

As an option for possible compensation for humus losses in crop rotation, green manure crops can be used in intercrops. With some approximation, we can assume that 1 ton of manure is compensated by 4 tons of green manure. So, if the green mass yield of green manure crops in intermediate crops is 20 t/ha, 1 ha of these crops compensates for 5 tons of manure. In our case, when all the by-products are harvested, the required area for sowing green manure is 0.48 hectares per 1 hectare of crop rotation. This indicates that in this case, almost half of the fields (48%) should be sown with green manure crops. In the case of alienation of the main part of by-products (straw and leaf and stem mass), full compensation of humus losses by sowing green manure crops is practically impossible, since the required area of green manure crops exceeds the actual area of crop rotation by almost 3 times (15.6/5).

Another measure to ensure a deficit-free balance of humus may be to obtain yield levels at which the humification of by-products that are worked into the soil can compensate for the loss of humus due to mineralization. Thus, if only stubble and roots are planted, the required compensatory yield is defined as:

$$Y_{OP} = \frac{LH}{\mathrm{CSR} \cdot KK \cdot CC}, \text{ t/ha} \qquad (55)$$

When all by-products are incorporated into the soil, this relationship is in the form:

$$Y_{\mathrm{OP}} = \frac{LH}{CSR \cdot CC}, \text{ t/ha} \qquad (56)$$

Table 40 shows the results of determining the necessary compensating yield levels for crops of a given crop rotation, provided that by-products are alienated and incorporated into the soil.

Table 40

The necessary levels of crop yields of crop rotation, which ensure a deficit-free balance of humus

Crop	Planned yield, t/ha	Required compensation yield, t/ha	
		When disposing of by-products	When wrapping by-products
Soybeans	2,6	11,9	5,5
Winter wheat	6,4	10,3	4,8
Corn for grain	7,3	12,4	5,2
Spring barley	3,2	11,4	5,6
Oats	3,0	10,9	5,5

Thus, if all by-products are harvested, only winter wheat and grain corn will have a surplus humus balance if the planned yield is achieved. That is, these crops create conditions for the accumulation of humus. Other crops have deficit conditions. It is clear that the possibility of forming the required compensatory yield level, as mentioned earlier, will depend on the moisture supply (M), soil type, intensity level of the variety or hybrid (RiC), the rate of mineral fertilizers (X) and the actual correlation between fertilizer prices (FP) and products (PP).

3. EXAMPLES OF CROP ROTATION ASSESSMENT BY DIFFERENT PRODUCTIVITY INDICATORS

Three crop rotations were selected for the evaluation:

1) seven-seeded - 1 peas, 2, 3 winter wheat, 4 corn for grain, 5 spring barley, 6 corn for grain, 7 sunflower;

2) four-seeded - 1 peas, 2 winter wheat, 3 corn for grain, 4 spring barley;

3) four-seeded - 1 pea, 2, 3 corn for grain, 4 spring barley.

The formalized structure of crops in the above crop rotations is presented in Table 41.

Table 41

Crop rotation structure to be assessed

Crop	Share of crops in crop rotation (α)		
	crop rotation 1	crop rotation 2	crop rotation 3
Soybeans	0,29	0,25	–
Winter wheat	0,14	0,25	0,25
Corn for grain	0,14	0,25	0,25
Spring barley	0,29	0,25	0,50
Oats	0,14	–	–

3.1. Without fertilization

3.1.1. Agroeconomic assessment

<u>Productivity per hectare of crop rotation area</u>

It is clear that the above dependencies (formulas (6a) and (7a)) determine the yield of a crop per 1 ha, and to determine the share of the crop in one hectare of crop rotation area, these values must be multiplied by the share of the crop in the crop rotation (αi).

Thus, all of the above allows us to assert that the harvest from a part of one hectare of crop rotation area is defined as

$$Y_B^{SP} = \alpha_i Y_n \qquad (57)$$

In other words, these data show that the highest yield per hectare of crop rotation area of grain units occurs in the first seven-manure crop rotation (33.3 c/ha), and the yields of the other four-manure crop rotations were the same and amounted to 32.4 c/ha (Table 42).

Table 42

Productivity of 1 hectare of crop rotation area of adopted crop rotations (B = 60 points)

Crop	Yields ($У_Б$), c/ha		Share of yield per hectare of crop rotation area ($Y_n^{SP} = \alpha_i Y$), c					
			Crop rotation 1		Crop rotation 2		Crop rotation 3	
	main products	grain unit	main products	grain unit	main products	grain unit	main products	grain unit
Winter wheat	36,9	36,9	10,7	10,7	9,2	9,2	–	–
Peas	21,0	29,5	2,9	4,1	5,2	7,4	5,2	7,4
Spring barley	32,9	29,5	4,6	3,7	8,2	6,6	8,2	6,6
Corn for grain	36,9	36,9	10,7	10,7	9,2	9,2	18,4	18,4
Sunflower	14,8	29,5	2,1	4,1	–	–	–	–
	–	–	–	Σ33,3	–	Σ32,4	–	Σ32,4

<u>By the cost of main products per hectare of crop rotation area</u>

The cost of the main product is determined by the purchase price (PP), and by analogy with the previous one, the cost of production per hectare of crop rotation is determined as the sum of the cost of harvesting all crops from one hectare of crop rotation area:

$$PC = 0{,}41B\Sigma(PP \cdot \alpha \cdot RiC/\text{К}_{3\text{O}})_i, UAH/ha. \qquad (58)$$

An example of calculating this indicator is shown in Table 43.

Table 43

An example of economic evaluation of one hectare of crop rotation area without fertilizers for different crop rotations

Crop	Purchase price (PP), UAH/c	Crop rotation 1		Crop rotation 2		Crop rotation 3	
		yield, t	cost, UAH	yield, t	cost, UAH	yield, t	cost, UAH
Winter wheat	180	10,7	1926	9,2	1656	–	–
Peas	250	2,9	725	5,2	1300	5,2	1300
Spring barley	160	4,6	736	8,2	1312	8,2	1312
Corn for grain	110	10,7	1177	9,2	1012	18,4	2024
Sunflower	800	2,1	1680	–	–	–	–
			Σ6244	–	Σ5280	–	Σ4636

According to economic indicators, the highest cost of production per hectare is expected in the first crop rotation (6244 UAH/ha), and the lowest - in the third (4636 UAH/ha).

3.1.2. Environmental assessment

<u>According to the humus balance deficit</u>

In general, humus losses per hectare of crop rotation can be defined as

$$L_H^{SP} = \Sigma(\alpha \cdot HL)t/ha. \qquad (59)$$

All calculations for determining humus losses are presented in Table 44.

Table 44

Example of calculations of humus losses due to mineralization in accepted crop rotations

Crop	Humus losses from 1 ha of crop sowing, t/ha	Humus losses from an equivalent part of 1 ha of crop rotation area, t		
		Crop rotation 1	Crop rotation 2	Crop rotation 3
Winter wheat	0,590	0,171	0,148	–
Peas	0,590	0,083	0,148	0,148
Spring barley	0,590	0,083	0,148	0,148
Corn for grain	1,201	0,348	0,300	0,600
Sunflower	1,201	0,168	–	–
	–	Σ0,853	Σ0,744	Σ0,896

The above suggests that the largest losses of humus occur in the third crop rotation (0.896 t/ha), and the smallest - in the second (0.744 t/ha)

Data on biomass supply and humus formation are presented in Tables 45, 46 and 47.

Table 45

Biomass supply and humus formation in the first crop rotation without fertilizers

Crop	Share of the main product harvest per 1 ha of crop rotation area, c	By-products, t			Humus, t	
		total	including			
			straw	stubble and roots	of all products	of all products
Winter wheat	10,7	15,0	8,0	7,0	0,300	0,140
Peas	2,9	3,8	2,0	1,8	0,080	0,037
Spring barley	4,6	5,1	2,6	2,5	0,102	0,050
Corn for grain	10,7	16,1	9,3	6,8	0,322	0,135
Sunflower	2,1	4,2	2,1	2,1	0,063	0,032
	–	Σ44,2	Σ24,0	Σ20,2	Σ0,867	Σ0,394

Table 46

Biomass supply and humus formation in the second crop rotation without fertilization

Crop	Share of main product harvest per hectare of crop rotation area, c	By-products, t			Humus, t	
		total	including			
			straw	stubble and roots	of all products	of all products
Winter wheat	9,2	12,9	6,8	6,1	0,258	0,122
Peas	5,2	6,8	3,6	3,2	0,143	0,066
Spring barley	8,2	9,0	4,6	4,4	0,180	0,088
Corn for grain	9,2	13,8	8,0	5,8	0,276	0,116
Sunflower	–	–	–	–	–	–
	–	Σ42,5	Σ23,0	Σ19,5	Σ0,857	Σ0,392

Table 47

Biomass supply and humus formation in the third crop rotation without fertilization

Crop	Share of main product harvest per hectare of crop rotation area, c	By-products, t			Humus, t	
		total	including			
			straw	stubble and roots	of all products	of all products
Winter wheat	–	–	–	–	–	–
Peas	5,2	6,8	3,6	3,2	0,143	0,066
Spring barley	8,2	9,0	4,6	4,4	0,180	0,088
Corn for grain	18,4	27,6	16,0	11,6	0,552	0,232
Sunflower	–	–	–	–	–	–
	–	Σ43,4	Σ24,2	Σ19,2	Σ0,875	Σ0,386

The humus balance for each of the crop rotations is shown in Tables 48, 49 and 50. It was found that while in the first and second crop rotations, when straw is incorporated, there is a certain surplus of humus, in the third there is a slight deficit. When straw is alienated, a deficit is observed in all cases.

For the shortage of basic nutrients

The calculations of the balance of the main nutrients in all three crop rotations are presented in Table 51.

Table 48

Humus balance in the first crop rotation in the variant without fertilization per 1 ha of area

Crop	Loss of humus, (*LH*), t	Humus supply (*GH*), t		Humus deficiency (HD = LH - HG), t/ha	
		with all by-products	with stubble and roots	with all by-products	with stubble and roots
Winter wheat	0,171	0,300	0,140	–0,129	0,031
Peas	0,083	0,080	0,037	0,003	0,046
Spring barley	0,083	0,102	0,050	–0,019	0,033
Corn for grain	0,348	0,322	0,135	0,026	0,213
Sunflower	0,168	0,063	0,032	0,105	0,136
	Σ0,853 t/ha	Σ0,867 t/ha	Σ0,394 t/ha	Σ-0,014 t/ha	Σ0,459 t/ha

Table 49

Humus balance in the second crop rotation in the variant without fertilization per 1 ha of area

Crop	Loss of humus, (*LH*), t	Humus supply (*GH*), t		Humus deficiency (HD = LH - HG), t/ha	
		with all by-products	with stubble and roots	with all by-products	with stubble and roots
Winter wheat	0,148	0,258	0,122	–0,110	0,026
Peas	0,148	0,143	0,066	0,005	0,082
Spring barley	0,148	0,180	0,088	–0,032	0,060
Corn for grain	0,300	0,276	0,116	0,024	0,184
Sunflower	–	–	–	–	–
	Σ0,744 t/ha	Σ0,857 t/ha	Σ0,392 t/ha	Σ–0,113 t/ha	Σ0,352 t/ha

Table 50

Humus balance in the third crop rotation in the variant without fertilization per 1 ha of area

Crop	Loss of humus, (*LH*), t	Humus supply (*GH*), t		Humus deficiency (HD = LH - HG), t/ha	
		with all by-products	with stubble and roots	with all by-products	with stubble and roots
Winter wheat	–	–	–	–	–
Peas	0,148	0,143	0,066	0,005	0,082
Spring barley	0,148	0,180	0,088	–0,032	0,060
Corn for grain	0,600	0,552	0,232	0,048	0,368
Sunflower	–	–	–	–	–
	Σ0,896 t/ha	Σ0,875 t/ha	Σ0,386 t/ha	Σ0,021 t/ha	Σ0,510 t/ha

Table 51

Losses (balance sheet deficit) ∑NPK in different crop rotations in the variant without fertilizers

Crop	Crop rotation 1			Crop rotation 2			Crop rotation 3		
	is the share of yield in 1 ha of crop rotation area, c	during straw harvesting, kg	when alienating straw, kg	is the share of yield in 1 ha of crop rotation area, c	during straw harvesting, kg	when alienating straw, kg	is the share of yield in 1 ha of crop rotation area, c	during straw harvesting, kg	when alienating straw, kg
Winter wheat	10,7	43,6	53,6	9,2	38,2	46,9	–	–	–
Peas	2,9	23,5	27,8	5,2	42,1	49,9	5,2	42,1	49,9
Spring barley	4,6	16,1	20,5	8,2	28,7	36,5	8,2	28,7	36,5
Corn for grain	10,7	30,5	66,6	9,2	26,2	57,2	18,4	52,4	114,4
Sunflower	2,1	10,4	26,3	–	–	–	–	–	–
	–	Σ124,1	Σ194,8	–	Σ135,2	Σ190,5	–	Σ123,2	Σ200,8

3.2. When applying 1 c a.i./ha of fertilizers

3.2.1. Agroeconomic assessment of the effectiveness of fertilizers themselves

In this case, according to the criteria defined in section 2.2, the amount of production of each crop per hectare of crop rotation area in each crop rotation is calculated in units of main products and in grain units (Table 52). After that, the value of additional products is determined for each crop rotation (Table 53).

Table 52

Agronomic evaluation of the efficiency of the first centner of fertilizers in different crop rotations

Crop	Yield increase, c/ha		Yield increase per equivalent area, c					
			Crop rotation 1		Crop rotation 2		Crop rotation 3	
	о.п.	з.о.	о.п.	з. о.	о.п.	з.о.	о.п.	з.о.
Winter wheat	10,92	10,92	3,17	3,17	2,73	2,73	–	–
Peas	5,47	7,66	0,77	1,07	1,37	1,91	1,37	1,91
Spring barley	5,41	4,33	0,76	0,61	1,35	1,08	1,35	1,08
Corn for grain	12,45	12,45	3,61	3,61	3,11	3,11	6,22	6,22
Sunflower	4,16	8,32	0,58	1,16	–	–	–	–
	–	–	–	Σ9,62	–	Σ8,83	–	Σ9,21

The data obtained show that the highest yield in grain units occurred in the first crop rotation (9.62 c g.u./ha), and the lowest in the second (8.83 c g.u./ha).

Table 53

Economic evaluation of the efficiency of the first centner of fertilizers in different crop rotations (by yield increase)

Crop	Purchase price, UAH/c	Crop rotation 1		Crop rotation 2		Crop rotation 3	
		yield, t	cost, UAH.	yield, t	cost, UAH.	yield, t	cost, UAH.
Winter wheat	180	3,17	570,6	2,73	491,4	–	–
Peas	250	0,77	192,5	1,37	342,5	1,37	342,5
Spring barley	160	0,76	121,6	1,35	217,6	1,35	217,6
Corn for grain	110	3,61	397,1	3,11	342,1	6,22	684,2
Sunflower	800	0,58	464,0	–		–	–
		–	Σ1745,8	–	Σ1393,6	–	Σ1244,3

At the current purchase prices, the cost of additional production per hectare of crop rotation area was the highest in the first crop rotation (1745.8 UAH), and the lowest in the third (1244.3 UAH). At the same time, by analogy with paragraph 2.2.1, it can be noted that if the cost of 1 centner of active substance together with the cost of application is about 1000 UAH, then only for all crop rotations the application of the first centner of mineral fertilizers is profitable with its value of 74.6-24.4%.

3.2.2. Agroeconomic assessment of crop efficiency when applying fertilizers

By analogy with the previous ones, Table 54 shows the economic assessment of the selected crop rotations with the application of 1 c з.о./ha. In this case, the yield of each crop was defined as the sum of the yields that can be formed due to natural soil fertility (YF) and the yield increase from fertilizer application (ΔY).

Table 54

Agroeconomic assessment of different crop rotations with 1 c/ha of mineral fertilizers

Crop	Crop rotation 1		Crop rotation 2		Crop rotation 3	
	harvest, c g.u.	cost, UAH	harvest, c g.u.	cost, UAH	harvest, c g.u.	cost, UAH
Winter wheat	13,87	2496,6	11,93	2147,4	–	–
Peas	5,17	917,5	9,31	1642,5	9,31	1642,5
Spring barley	4,31	857,6	7,68	1529,6	7,68	1529,6
Corn for grain	14,31	1574,1	12,31	1354,1	24,62	2708,2
Sunflower	5,26	2144,0	–	–	–	–
	Σ42,92	Σ7989,8	Σ41,23	Σ6673,6	Σ41,61	Σ5880,3

The results suggest that in the case of fertilizer application at a rate of 100 kg/ha, the first crop rotation is the best in terms of the highest income, and the third is the worst.

3.2.3. Environmental assessment

According to the humus balance deficit

The results of the environmental assessment of the three crop rotations are presented in Tables 55a-56c.

Table 55a

Biomass supply and humus formation in the first crop rotation at a fertilizer rate of 100 kg/ha

Crop	Share of the main product harvest per 1 ha of crop rotation area, c	By-products, t			Humus, t	
		total	у т.ч.			
			straw	stubble and roots	of all products	from stubble and roots
Winter wheat	13,9	19,5	10,3	9,2	0,390	0,184
Peas	3,7	4,8	2,6	2,2	0,101	0,046
Spring barley	5,4	5,9	3,0	2,9	0,118	0,058
Corn for grain	14,3	21,5	12,4	9,1	0,430	0,182
Sunflower	2,7	5,4	2,7	2,7	0,081	0,041
	–	Σ57,1	Σ31,0	Σ27,1	Σ1,120	Σ0,511

Table 55b

Biomass supply and humus formation in the second crop rotation at a fertilizer rate of 100 kg/ha

Crop	Share of the main product harvest per 1 ha of crop rotation area, c	By-products, t			Humus, t	
		total	у т.ч.			
			straw	stubble and roots	of all products	from stubble and roots
Winter wheat	11,9	17,2	9,1	8,1	0,344	0,162
Peas	6,6	8,6	4,6	4,0	0,181	0,084
Spring barley	9,6	10,6	5,4	5,2	0,216	0,104
Corn for grain	12,3	18,5	10,7	7,8	0,370	0,156
Sunflower	–	–	–	–	–	–
	–	Σ54,9	Σ29,8	Σ25,1	Σ1,111	Σ0,506

Table 55c

Biomass supply and humus formation in the third crop rotation at a fertilizer rate of 100 kg/ha

Crop	Share of the main product harvest per 1 ha of crop rotation area, c	By-products, t			Humus, t	
		total	у т.ч.		of all products	from stubble and roots
			straw	stubble and roots		
Winter wheat	–	–	–	–	–	–
Peas	6,6	8,6	4,6	4,0	0,181	0,084
Spring barley	9,6	10,6	5,4	5,2	0,216	0,104
Corn for grain	24,6	37,0	21,4	15,6	0,740	0,312
Sunflower	–	–	–	–	–	–
	–	Σ56,2	Σ31,4	Σ24,8	Σ1,137	Σ0,500

Table 56a

Humus balance in the first crop rotation when applying 1 c of fertilizer per 1 ha of crop rotation area

Crop	Loss of humus, (*LH*), t	Humus supply (*GH*), t		Humus deficiency (HD = LH - HG), t/ha	
		with all the by-products	with stubble and roots	with all the by-products	with stubble and roots
Winter wheat	0,171	0,390	0,184	–0,219	–0,013
Peas	0,083	0,101	0,046	–0,018	0,037
Spring barley	0,083	0,118	0,058	–0,035	0,025
Corn for grain	0,348	0,430	0,182	–0,082	0,166
Sunflower	0,168	0,081	0,041	0,087	0,127
	Σ0,853 t/ha	Σ1,120 t/ha	Σ0,511 t/ha	–0,267 t/ha	0,342 t/ha

Table 56b

Humus balance in the second crop rotation when applying 1 c of fertilizer per 1 ha of crop rotation area

Crop	Loss of humus, (*LH*), t	Humus supply (*GH*), t		Humus deficiency (HD = LH - HG), t/ha	
		with all the by-products	with stubble and roots	with all the by-products	with stubble and roots
Winter wheat	0,148	0,344	0,162	–0,196	–0,014
Peas	0,148	0,181	0,084	–0,033	0,064
Spring barley	0,148	0,216	0,104	–0,068	0,044
Corn for grain	0,300	0,370	0,156	–0,070	0,144
Sunflower	–	–	–	–	–
	Σ0,744 t/ha	Σ1,111 t/ha	Σ0,506 t/ha	Σ-0,367 t/ha	Σ0,238 t/ha

Table 56c

Humus balance in the third crop rotation when applying 1 c of fertilizer per 1 ha of crop rotation area

Crop	Loss of humus, (*LH*), t	Humus supply (*GH*), t		Humus deficiency (HD = LH - HG), t/ha	
		with all the by-products	with stubble and roots	with all the by-products	with stubble and roots
Winter wheat	–	–	–	–	–
Peas	0,148	0,181	0,084	–0,033	0,064
Spring barley	0,148	0,216	0,104	–0,068	0,044
Corn for grain	0,600	0,740	0,312	–0,140	0,288
Sunflower	–	–	–	–	–
	Σ0,896 t/ha	Σ1,137 t/ha	Σ0,500 t/ha	Σ–0,241 t/ha	Σ0,396 t/ha

Thus, the application of mineral fertilizers at a rate of 1 c a.i./ha not only increases yields and provides an increase in agroeconomic efficiency, but also significantly affects the humus balance. Thus, in this case, for all three crop rotations, when straw is incorporated into the soil, there is a surplus of humus balance, and when it is alienated, the balance deficit is significantly reduced.

For the shortage of basic nutrients

The calculations of the balance of the main nutrients in all three crop rotations are carried out by analogy with the previous one, with the supply of elements being 100 kg as the norm for their application. The results of such determinations are shown in Tables 57 - 58c.

Table 57

Losses ∑NPK in different crop rotations in the variant of fertilizer application rate of 100 kg/ha

Crop	Crop rotation 1			Crop rotation 2			Crop rotation 3		
	when alienating straw, kg	is the share of yield in 1 ha of crop rotation area, c	during straw harvesting, kg	when alienating straw, kg	is the share of yield in 1 ha of crop rotation area, c	during straw harvesting, kg	when alienating straw, kg	при загортанні соломи, кг	при відчуженні соломи, кг
Winter wheat	13,9	57,7	70,9	11,9	49,4	60,7	–	–	–
Peas	3,7	30,0	35,5	6,6	53,5	63,4	6,6	53,5	63,4
Spring barley	5,4	18,9	24,0	9,6	33,6	42,7	9,6	33,6	42,7
Corn for grain	14,3	40,8	88,9	12,3	30,1	76,5	24,6	60,2	153,0
Sunflower	2,7	13,4	33,8	–	–	–	–	–	–
	–	Σ160,8	Σ253,1	–	Σ166,6	Σ243,3	–	Σ147,3	Σ259,1

Table 58a

Balance of ∑NPK in the first crop rotation when applying 1 c of fertilizer per 1 ha of crop rotation area

Crop	Revenues. ΣNPK (H_E), kg	Losses ΣNPK(B_E), kg		Deficit ΣNPK ($D_E = B_E - H_E$), kg	
		during straw harvesting, kg	when alienating straw, kg	with all by-products	with stubble and roots
Winter wheat	29	57,7	70,9	28,7	41,9
Peas	14	30,0	35,5	16,0	21,5
Spring barley	14	18,9	24,0	4,9	10,0
Corn for grain	29	40,8	88,9	11,8	59,9
Sunflower	14	13,4	33,8	–0,6	19,8
	Σ100	Σ160,8	Σ253,1	Σ60,8	Σ153,1

Table 58b

Balance of ∑NPK in the second crop rotation when applying 1 c of fertilizer per 1 ha of crop rotation area

Crop	Revenues. ΣNPK (H_E), kg	Losses ΣNPK(B_E), kg		Deficit ΣNPK ($D_E = B_E - H_E$), kg	
		during straw harvesting, kg	when alienating straw, kg	with all by-products	with stubble and roots
Winter wheat	25	49,4	60,7	24,4	35,7
Peas	25	53,5	63,4	28,5	38,4
Spring barley	25	33,6	42,7	8,6	17,7
Corn for grain	25	30,1	76,5	5,1	51,5
Sunflower	–	–	–		
	Σ100	Σ166,6	Σ243,3	Σ66,6	Σ143,3

Table 58c

Balance of ∑NPK in the third crop rotation when applying 1 c of fertilizer per 1 ha of crop rotation area

Crop	Revenues. ΣNPK (H_E), kg	Losses ΣNPK(B_E), kg		Deficit ΣNPK ($D_E = B_E – H_E$), kg	
		during straw harvesting, kg	when alienating straw, kg	with all by-products	with stubble and roots
Winter wheat	–	–	–	–	–
Peas	25	53,5	63,4	28,5	38,4
Spring barley	25	33,6	42,7	8,6	17,7
Corn for grain	50	60,2	153,0	10,2	103,0
Sunflower	–	–	–		
	Σ100	Σ147,3	Σ259,1	Σ47,3	Σ159,1

The calculations showed that at a fertilizer rate of 100 kg/ha, the loss of basic elements from the soil increases, but the deficit of these elements in each crop rotation is significantly reduced, although it remains significant.

3.3 Evaluation of crop rotations under the condition of ensuring the absence of deficiency of basic elements in the soil

In these calculations, by analogy with the previous ones, the amount of fertilizer per area occupied by a given crop per 1 hectare of crop rotation area (αi), as well as the yield increase from a given amount of fertilizer, was determined depending on the structure of crops in the crop rotation. In this case, the basis for further calculations is the data in Table 27.

Given that this calculation option assumes no deficit of basic nutrients, further determinations are based on agroeconomic indicators (Tables 59a-60b) and environmental indicators by humus balance (Tables 61a-62).

Table 59a

Agroeconomic assessment of the first crop rotation with the application of a deficit-free rate of mineral fertilizers per 1 ha of area

Crop	Crop share in crop rotation	Non-deficit fertilizer rate, a.i.		Increase in the harvest of main products, c		Yield increase in grain units, tons		Cost of additional products, UAH	
		when wrapping straw	when alienating straw	when wrapping straw	when alienating straw	when wrapping straw	when alienating straw	when wrapping straw	when alienating straw
Winter wheat	0,290	0,702	0,902	6,21	6,99	6,21	6,99	1142,1	1258,2
Peas	0,140	0,358	0,435	1,48	1,60	2,07	2,24	370,0	400,0
Spring barley	0,140	0,196	0,367	0,99	3,64	0,79	2,91	158,4	502,4
Corn for grain	0,290	0,455	1,259	5,28	9,54	5,28	9,54	580,8	1049,4
Sunflower	0,140	0,129	0,420	0,55	1,30	1,10	2,60	880,0	2080,0
	Σ1,00	Σ1,840	Σ3,383	–	–	Σ15,45	Σ24,28	Σ3131,3	Σ5290,0

Table 59b

Agroeconomic assessment of the second crop rotation with the application of a deficit-free rate of mineral fertilizers per 1 ha of area

Crop	Crop share in crop rotation	Non-deficit fertilizer rate, a.i.		Increase in the harvest of main products, c		Yield increase in grain units, tons		Cost of additional products, UAH	
		when wrapping straw	when alienating straw	when wrapping straw	when alienating straw	when wrapping straw	when alienating straw	when wrapping straw	when alienating straw
Winter wheat	0,250	0,605	0,778	5,35	6,02	5,35	6,02	963,0	1083,6
Peas	0,250	0,640	0,778	2,65	2,85	3,71	3,99	662,5	712,5
Spring barley	0,250	0,350	0,655	1,78	6,50	1,42	5,20	284,8	1040,0
Corn for grain	0,250	0,392	1,085	4,55	8,22	4,55	8,22	500,5	904,2
Sunflower	–	–	–	–	–	–	–	–	–
	Σ1,00	Σ1,987	Σ3,296	–	–	Σ15,03	Σ23,43	Σ2410,8	Σ3740,3

Таблиця 59c

Agroeconomic assessment of the third crop rotation with the application of a deficit-free rate of mineral fertilizers per 1 ha of area

Crop	Crop share in crop rotation	Non-deficit fertilizer rate, a.i.		Increase in the harvest of main products, c		Yield increase in grain units, tons		Cost of additional products, UAH	
		when wrapping straw	when alienating straw	when wrapping straw	when alienating straw	when wrapping straw	when alienating straw	when wrapping straw	when alienating straw
Winter wheat	–	–	–	–	–	–	–	–	–
Peas	0,250	0,640	0,778	2,65	2,85	3,71	3,99	662,5	712,5
Spring barley	0,250	0,350	0,655	1,78	6,50	1,42	5,20	284,8	1040,0
Corn for grain	0,500	0,784	2,170	9,10	16,44	9,10	16,44	1001,0	1808,4
Sunflower	–	–	–	–	–	–	–	–	–
	Σ1,00	Σ1,774	Σ3,603	–	–	Σ14,23	Σ25,63	Σ1948,3	Σ3560,9

Table 60a

Agroeconomic assessment of different crop rotations with the application of a deficit-free rate of mineral fertilizers (when straw is harvested)

Crop	Crop rotation 1		Crop rotation 2		Crop rotation 3	
	harvest, c g.u.	cost, UAH	harvest, c g.u.	cost, UAH	harvest, c g.u.	cost, UAH
Winter wheat	16,91	3068,1	14,55	2619,0	–	–
Peas	6,17	1095,0	11,11	1962,5	11,11	1962,5
Spring barley	4,49	894,4	8,02	1596,8	8,02	1596,8
Corn for grain	15,98	1757,1	13,75	1512,5	27,50	3025,0
Sunflower	5,20	2560,0	–	–	–	–
	Σ48,75	Σ9374,6	Σ47,43	Σ7690,8	Σ46,63	Σ6584,3

Table 60b

Agroeconomic assessment of different crop rotations with the application of a deficit-free rate of mineral fertilizers (with straw alienation)

Crop	Crop rotation 1		Crop rotation 2		Crop rotation 3	
	harvest, c g.u.	cost, UAH	harvest, c g.u.	cost, UAH	harvest, c g.u.	cost, UAH
Winter wheat	17,69	3184,2	15,22	2739,6	–	–
Peas	6,34	1125,0	11,39	2012,5	11,39	2012,5
Spring barley	6,61	1238,4	11,80	2352,0	11,80	2352,0
Corn for grain	20,24	2226,4	17,42	1916,2	34,84	3832,4
Sunflower	6,70	3760,0	–	–	–	–
	Σ57,58	Σ11534,0	Σ55,83	Σ9020,3	Σ58,03	Σ8196,9

Table 61a

Biomass intake and humus formation in the first crop rotation under non-deficit fertilizer rate

Crop	When wrapping straw			When alienating straw		
	is the share of yield in 1 ha of area, c	by-products (all), t	formed humus, t	is the share of yield in 1 ha of area, c	harvested by-products (stubble and roots), t	formed humus, t
Winter wheat	16,9	23,7	0,473	17,7	11,6	0,233
Peas	4,4	5,7	0,120	4,5	2,7	0,056
Spring barley	5,6	6,2	0,124	8,2	4,4	0,088
Corn for grain	16,0	24,0	0,480	20,2	12,7	0,254
Sunflower	2,6	5,2	0,078	3,3	3,3	0,050
	–	Σ64,8	Σ1,275	–	Σ34,7	Σ0,681

Table 61b

Biomass supply and humus formation in the second crop rotation under non-deficit fertilizer rate

Crop	When wrapping straw			When alienating straw		
	is the share of yield in 1 ha of area, c	by-products (all), t	formed humus, t	is the share of yield in 1 ha of area, c	harvested by-products (stubble and roots), t	formed humus, t
Winter wheat	14,6	21,1	0,422	15,2	10,0	0,200
Peas	7,9	10,3	0,154	8,1	4,8	0,073
Spring barley	10,0	11,0	0,220	14,7	7,9	0,158
Corn for grain	13,8	20,7	0,414	17,4	11,0	0,220
Sunflower	–	–	–	–	–	–
		Σ3,1	Σ1,210	–	Σ32,7	Σ0,651

Table 61c

Biomass supply and humus formation in the third crop rotation with no fertilizer deficit

Crop	When wrapping straw			When alienating straw		
	is the share of yield in 1 ha of area, c	by-products (all), t	formed humus, t	is the share of yield in 1 ha of area, c	harvested by-products (stubble and roots), t	formed humus, t
Winter wheat	–	–	–	–	–	–
Peas	7,9	10,3	0,154	8,1	4,8	0,073
Spring barley	10,0	11,0	0,220	14,7	7,9	0,158
Corn for grain	27,6	41,4	0,828	34,9	22,0	0,440
Sunflower	–	–	–	–	–	–
		Σ62,7	Σ1,202		Σ34,7	Σ0,671

Table 62

Calculation of humus balance for different crop rotations with no deficit fertilizer rate

Crop	Loss of humus, (*LH*), t	When wrapping straw		When alienating straw	
		humus supply (HS), t	deficit (DH), t	humus supply (HS), t	deficit (DH), t
I crop rotation					
Winter wheat	0,171	0,473	–0,302	0,233	–0,062
Peas	0,083	0,120	–0,037	0,056	0,027
Spring barley	0,083	0,124	–0,041	0,088	–0,005
Corn for grain	0,348	0,480	–0,132	0,254	0,094
Sunflower	0,168	0,078	0,090	0,050	0,118
	Σ0,853	Σ1,275	Σ–0,422	Σ0,681	Σ0,172
II crop rotation					
Winter wheat	0,148	0,422	–0,274	0,200	–0,052
Peas	0,148	0,154	–0,006	0,073	0,075
Spring barley	0,148	0,220	–0,072	0,158	–0,010
Corn for grain	0,300	0,414	–0,114	0,220	0,080
Sunflower	–	–	–	–	–
	Σ0,744	Σ1,210	Σ–0,466	Σ0,651	Σ0,093
III crop rotation					
Winter wheat	–	–	–	–	–
Peas	0,148	0,154	–0,006	0,073	0,075
Spring barley	0,148	0,220	–0,072	0,158	–0,010
Corn for grain	0,600	0,828	–0,228	0,440	0,160
Sunflower	–	–	–	–	–
	Σ0,896	Σ1,202	Σ–0,306	Σ0,671	Σ0,225

3.4 Integral assessment of crop rotations by specific indicators and intensity of individual crops

The results of the definitions presented in Table 63 allow for an objective assessment of the above crop rotations, and, if necessary, to determine one of them according to certain criteria.

Table 63

Generalized indicators for the evaluation of these crop rotations per 1 ha of crop rotation area

Terms and conditions	First crop rotation	Second crop rotation	Third crop rotation
1	2	3	4
When growing without fertilizers			
Productivity, c g.u.ha	33,3	32,4	32,4
Cost of production, UAH/ha	6244	5280	4636
Deficit of humus balance, t/ha - when plowing straw into the soil - when alienating straw	 –0,014 0,459	 –0,113 0,352	 0,021 0,510
Compensation area (relative) for green manure crops: - when plowing straw into the soil - when alienating straw	 – 0,57	 – 0,44	 0,03 0,64
Deficit of NPK balance, kg/ha: - when plowing straw into the soil - when alienating straw	 124,1 194,8	 135,2 190,5	 123,2 200,8
At suction of 1 (first) c .a.i./ha			
Additional performance, c g.u.ha	9,6	8,8	9,2
Cost of additional products, UAH/ha	1746	1394	1244
Productivity, c g.u./ha	42,9	41,2	41,6
Cost of production, UAH/ha	7990	6674	5880
Terms and conditions	The first crop rotation	The second crop rotation	The third crop rotation
Deficit of humus balance, t/ha: - when plowing straw into the soil - when alienating straw	 –0,267 0,342	 –0,367 0,238	 –0,241 0,396
Compensation area (relative) for green manure crops: - when plowing straw into the soil - when alienating straw	 – 0,43	 – 0,30	 – 0,0,49

Table continuation 63

1	2	3	4
Deficit of NPK balance, kg/ha: - when plowing straw into the soil - when alienating straw	 60,8 153,1	 66,6 143,3	 47,3 159,1
The rate of mineral fertilizers that ensures a deficit-free balance of NPK, c a.i./ha:			
- when plowing straw into the soil - when alienating straw	1,840 3,383	1,987 3,296	1,774 3,603
Additional productivity, d.m./ha: - when plowing straw into the soil - when alienating straw	 15,4 24,3	 15,0 23,4	 14,2 25,6
Cost of additional production, UAH/ha: - when plowing straw into the soil - when alienating straw	3131 5290	2411 3740	1948 3561
Productivity, d.m./ha: - when plowing straw into the soil - at straw alienation	 48,7 57,6	 47,4 55,8	 46,6 58,0
Cost of production, UAH/ha: - when plowing straw into the soil - when alienating straw	 9375 11534	 7691 9020	 6584 8197
Deficit of humus balance, t/ha: - when plowing straw into the soil - when alienating straw	 –0,422 0,172	 –0,426 0,093	 –0,306 0,225
Compensation area (relative) for green manure crops: - when plowing straw into the soil - when alienating straw	 – 0,22	 – 0,12	 – 0,28

Based on the data obtained, it can be argued that in terms of productivity per hectare of crop rotation area (c a.i./ha) and product value (UAH/ha), the best indicators are usually recorded in the first crop rotation. The second crop rotation is characterized by the best results in terms of humus balance deficit both when straw is alienated and when it is wrapped. Regarding the balance of NPK, it was found that in the case of incorporating straw into the soil, the best indicators are characteristic of the third crop rotation, and in the case of its alienation - in the second.

One of the options to compensate for the loss of humus from straw alienation may be the cultivation of green manure crops in intercrops. It is known that when green manure crops are incorporated into the soil, humus is formed in the amount of about 4% of the green manure yield [6, 11]. Thus, with a green mass yield of green manure crops of 180-200 c/ha, the amount of newly formed humus is 0.72-0.80 t/ha. The cost of this measure is the technological cost of growing green manure.

Thus, the calculations show that in the case of a deficit of humus balance during straw alienation, the area of green manure crops required to ensure a deficit-free humus balance varies in different variants within 44-64%, in the variant of cultivation without fertilization up to 12-28%, in the variant of fertilization - under the condition of no NPK deficit (see Table 63). At the same time, it is clear that the required areas for green manure and the possible areas in each crop rotation are consistent. In other words, the most favorable situation is when green manure crops are grown after cereal crops, the area of which is accepted in the crop rotation.

There is no doubt that the best option in terms of environmental friendliness for all crop rotations is the option of applying a deficit-free rate of NRC, while the compensation area for green manure crops is the smallest and generally consistent with the possibility of growing them.

In the individual assessment of crop productivity in crop rotation, the problem is to compare the area under the crop (αi) and the share of this crop indicator in the total amount ($\beta_i = \frac{P_i}{\Sigma P}$), which can characterize the intensity of crop productivity (ICP). In this case, the normative value of this indicator should be 1.0. This means that if the crop occupies 20% of the field area in the crop rotation, then its production in the total amount is also 25%. For example, Table 32 shows that the productivity of 1 ha of crop rotation area in the first crop rotation without fertilization is 33.3 c a.i./ha (∑P), and the productivity of winter wheat is 10.7 c d.m./ha (Pi). Thus, the share of winter wheat (βi) is 0.321 (10.7/33.3) (Table 64). This shows that the crop occupies an area of 29% and produces 32.1% of the total amount, i.e. the intensity of this crop in the crop rotation (IPC) is higher than the normative one and amounts to 1.107.

The analysis of the data shows that according to the criterion of productivity (a.i./ha) in all variants of fertilizer application and in all crop rotations, winter wheat and corn are characterized by the highest intensity (IPC > 1). Regarding the cost of production (UAH/ha) of the crop, it can be noted that while in the first and second crop rotations in the variant without fertilization and at their rate of 1 c/ha, the highest indicators are characterized by sunflower and winter wheat, in the third - peas and barley. At a break-even rate of mineral fertilizers with high productivity of sunflower and wheat in the second and third crop rotation, the relative productivity of peas increases when straw is incorporated, and spring barley increases when it is alienated.

In general, there is no doubt that, all other things being equal, the productivity and crop rotation of a crop as a whole and of individual crops will depend significantly on the adopted intensity of the variety and the purchase price of the product. Consequently, for the same crop rotations and the same natural and climatic conditions, with different values of these indicators, their characteristics may be significantly different.

There is also no doubt that individual assessment of crop intensity can be carried out using both the components of the humus balance and the ∑NPK balance.

Table 64

Оцінка інтенсивності сільськогосподарських культур в окремих сівозмінах за агроекономічними показниками

Crop	The first crop rotation			The second crop rotation			The third crop rotation		
	area share	share of the indicator	intensity	area share	share of the indicator	intensity	area share	share of the indicator	intensity
In the variant without fertilization *a) by productivity, c з.о./ha*									
Winter wheat	0,29	0,321	1,107	0,25	0,284	1,136	–	–	–
Peas	0,14	0,123	0,879	0,25	0,218	0,912	0,25	0,218	0,912
Spring barley	0,14	0,110	0,794	025	0,204	0,815	0,25	0,204	0,815
Corn for grain	0,29	0,321	1,107	0,25	0,284	1,136	0,50	0,568	1,136
Sunflower	0,14	0,123	0,879	–	–	–	–	–	–
b) by value of production, UAH/ha									
Winter wheat	0,29	0,308	1,064	0,25	0,314	1,255	–	–	–
Peas	0,14	0,116	0,829	0,25	0,246	0,985	0,25	0,280	1,122
Spring barley	0,14	0,118	0,842	025	0,248	0,994	0,25	0,283	1,132
Corn for grain	0,29	0,189	0,650	0,25	0,192	0,767	0,50	0,437	0,873
Sunflower	0,14	0,269	1,921	–	–	–	–	–	–
At a fertilizer rate of 1 c a.i./ha *a) by productivity, c з.о./ha*									
Winter wheat	0,29	0,323	1,114	0,25	0,289	1,157	–	–	–
Peas	0,14	0,120	0,860	0,25	0,226	0,903	0,25	0,224	0,895

Table continuation 64

Crop	The first crop rotation			The second crop rotation			The third crop rotation		
	area share	share of the indicator	intensity	area share	share of the indicator	intensity	area share	share of the indicator	intensity
Spring barley	0,14	0,100	0,717	025	0,186	0,745	0,25	0,185	0,738
Corn for grain	0,29	0,333	1,150	0,25	0,29*9	1,194	0,50	0,592	1,183
Sunflower	0,14	0,123	0,875	–	–	–	–	–	–
b) by value of production, UAH/ha									
Winter wheat	0,29	0,313	1,078	0,25	0,312	1,287	–	–	–
Peas	0,14	0,116	0,821	0,25	0,246	0,984	0,25	0,279	1,117
Spring barley	0,14	0,107	0,767	025	0,223	0,917	0,25	0,260	1,040
Corn for grain	0,29	0,197	0,679	0,25	0,203	0,812	0,50	0,460	0,921
Sunflower	0,14	0,268	1,917	–	–	–	–	–	–
At a break-even fertilizer rate (when straw is incorporated) *a) by productivity, c з.о./ha*									
Winter wheat	0,29	0,347	1,196	0,25	0,307	1,227	–	–	–
Peas	0,14	0,127	0,904	0,25	0,234	0,937	0,25	0,238	0,953
Spring barley	0,14	0,062	0,658	025	0,169	0,676	0,25	0,172	0,688
Corn for grain	0,29	0,328	1,130	0,25	0,290	1,160	0,50	0,590	1,180
Sunflower	0,14	0,107	0,762	–	–	–	–	–	–

Table continuation 64

Crop	The first crop rotation			The second crop rotation			The third crop rotation		
	area share	share of the indicator	intensity	area share	share of the indicator	intensity	area share	share of the indicator	intensity
b) by value of production, UAH/ha									
Winter wheat	0,29	0,327	1,128	0,25	0,341	1,362	–	–	–
Peas	0,14	0,117	0,834	0,25	0,255	1,020	0,25	0,298	1,192
Spring barley	0,14	0,095	0,681	025	0,207	0,831	0,25	0,242	0,970
Corn for grain	0,29	0,187	0,646	0,25	0,1+7	0,786	0,50	0,459	0,919
Sunflower	0,14	0,273	1,950	–	–	–	–	–	–
At a break-even fertilizer rate (when straw is alienated) *a) by productivity, c з.о./ha*									
Winter wheat	0,29	0,307	1,059	0,25	0,273	1,090	–	–	
Peas	0,14	0,110	0,786	0,25	0,204	0,816	0,25	0,196	0,786
Spring barley	0,14	0,115	0,820	025	0,215	0,846	0,25	0,203	0,814
Corn for grain	0,29	0,352	1,212	0,25	0,312	1,076	0,50	0,601	1,201
Sunflower	0,14	0,116	0,829	–	–	–	–	–	
b) by value of production, UAH/ha									
Winter wheat	0,29	0,276	0,952	0,25	0,304	1,215	–	–	
Peas	0,14	0,098	0,697	0,25	0,223	0,892	0,25	0,245	0,982
Spring barley	0,14	0,107	0,767	025	0,261	1,042	0,25	0,287	1,148
Corn for grain	0,29	0,193	0,665	0,25	0,212	0,850	0,50	0,467	0,935
Sunflower	0,14	0,326	2,328	–	–	–	–	–	

4. ECONOMIC ASPECTS OF CROP ROTATION ASSESSMENT

A comparative assessment of crop rotations conducted in one way or another requires additional economic justification for the decisions made. In general, it can be argued that economic analysis is the determination of net income, profitability and production costs both separately for each crop and by crop rotation. However, such an analysis is largely time-bound, as it requires annual consideration of prices for fertilizers, seeds, pesticides, and fuel and lubricants due to their volatility.

In general, in our case, such decisions are based on three components that need to be determined: technological costs of growing crops, costs of growing green manure, and costs of fertilizing.

Fertilization (use of mineral fertilizers) requires a separate assessment of the technological costs of growing crops in crop rotation, which is caused by the not always favorable price ratio of fertilizers and products. The main requirement here is to avoid a situation where the use of fertilizers is unprofitable [21, 28]. Technological costs themselves, while relatively constant in terms of the list of operations, may vary in size depending on agricultural machinery and plant protection products and are generally individual for each farm or agricultural company.

The costs of growing green manure crops are shown in Table 65.

Thus, the total additional technological costs for growing green manure crops (without stubble peeling and plowing) amount to 658.90 UAH/ha, and taking into account the required or accepted profitability of this compensation measure, its cost will be 856.7 UAH (658.9*1.3). It is clear that in this case, only variable costs are taken into account, since fixed costs are not taken into account, which together somewhat reduces the actual costs.

Table 65

Technological costs of growing post-harvest oil radish green manure [6, 26]

Technological operations	Salary costs, UAH/ha	Fuels and lubricants	
		l/ha	UAH/ha for C_P = = 10,84 UAH/l
Stubble peeling 6-8 cm in two traces*	5,48	4,4	47,70
Loading fertilizers and seeds	9,77	0,3	3,25
Transportation of fertilizers and seeds	6,68	2,0	21,68
Sowing of SZT-3,6	18,91	2,9	31,44
Rolling	4,74	2,9	31,44
Cost of seeds (30 kg/ha of oil radish)	210,0		
Cost of fertilizers (100 kg/ha of ammonium nitrate in physical weight)	321,0		
Plowing to a depth of 27-30 cm*	27,66	23,10	250,40
Total	**604,24**	**35,6**	**385,90**

* - operations that are necessary even without growing green manure

The most important thing, in our opinion, is the economic justification of mineral fertilizers. Since fertilizer rates are determined by the criterion of non-scarcity in terms of the NRK, the problem is to determine the increase from this rate and the necessary ratio of prices for fertilizers themselves (FD) and products (PP). In this case, the final determination is a comparison of the value of additional production (VAP) and the cost of fertilizer application (CA).

As is well known, the value of additional production is the product of the yield increase (ΔY) and the product price (PP). The value of the yield increase can be determined from the condition of declining yield, which, together with the accepted or established level of variety intensity (RiC), is determined by formula (12) [1, 21, 28].

It should be noted that due to the additional costs of harvesting and processing this additional crop, it is necessary to take into account additional costs. One of the options for such accounting may be to apply a reduction factor of at least 0.9 [1, 21, 28]. This means that the additional costs of harvesting the incremental yield do not exceed 10% of its price (CP). Taking into account all the above, the cost of additional yield (ΔY) from the application of fertilizer rate (X) can be defined as

$$CAY = 0{,}9\Delta Y \cdot C_{ПР} = 0{,}9C_P \cdot RiC(aX^2 + вX), \text{ UAH/ha} \quad (60)$$

The cost of using fertilizers depends on their price and the cost of additional activities, including transportation, application, storage, etc. In general, it can be assumed that they do not exceed 10% of their price (CP), which allows us to define the cost of fertilizer application as [1, 21, 25].

$$CF = 1{,}1X \cdot C_F, \text{ UAH/ha} \quad (61)$$

Thus, the relationship between these indicators (GI and GVA) is the main condition for determining the necessary ratio of fertilizer prices to product prices. However, given the indirect linear dependence of yield growth on fertilizer application, there is a problem with the amount of fertilizer or its rate (X).

The essence of the proposed definitions is to set the maximum possible (critical) prices for mineral fertilizers depending on product prices and fertilizer application rates or the corresponding yield increase.

An illustration of the above is shown in Fig. 4.

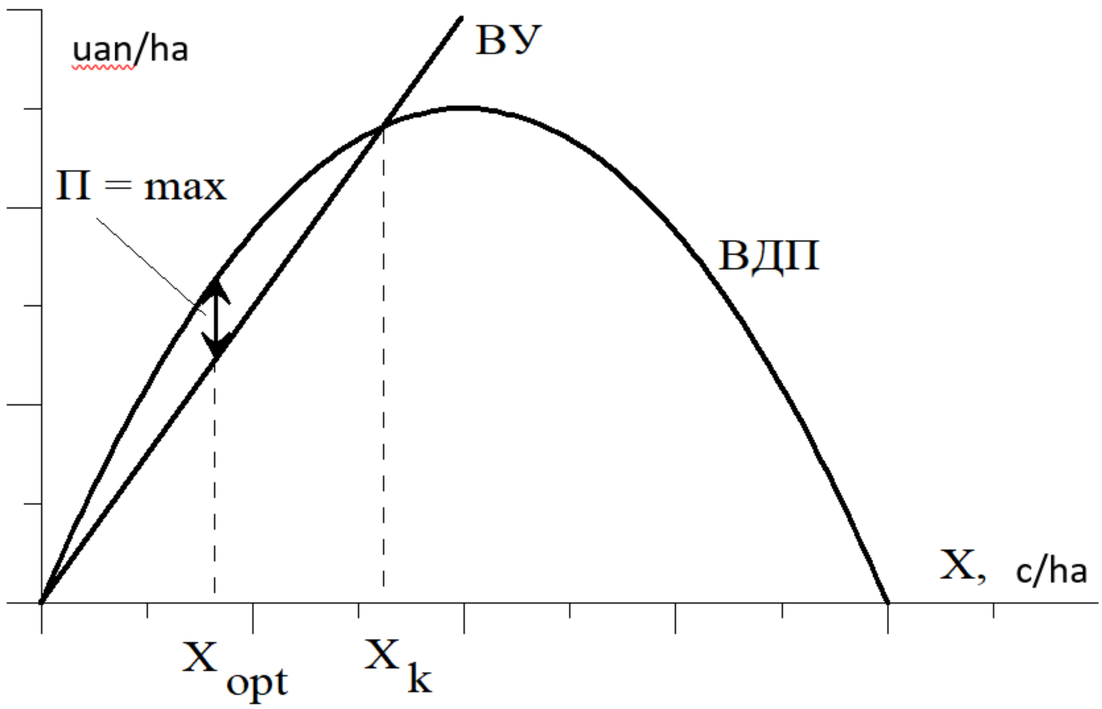

Fig. 4. Scheme for determining the effectiveness of mineral fertilizers

This indicates that, given known or assumed prices for fertilizers and products, the above dependencies are in place, since when any price changes, the corresponding dependencies change. In general, there can be two criteria with different kinds of restrictions: maximum profit and breakeven.

1. When assessing performance according to the maximum profit criterion, the essence of the constraints is to determine the most possible value of the fertilizer price at different product prices and different fertilizer rates, at which the profit will be maximized (Xopt):

$$P = CAY - PF = max \text{ або } 0{,}9C_P(aX^2 + вX) - 1{,}1X \cdot PF \quad = max \quad (62)$$

This condition is possible according to [21].

$$X = X_{opt} = -\frac{(0{,}9в \cdot RiC \cdot P_F - 1{,}1P_F)}{1{,}8a \cdot RiC \cdot P_F}, c\ a.i./ha \qquad (63)$$

2. When assessing performance against the break-even criterion, the essence of the constraints is to determine the most possible value of the fertilizer price at different product prices and different fertilizer rates, at which there will be no losses, i.e., the profit will be at least zero (HC):

$$P = CAY - PF \geq 0 \text{ або } 0{,}9C_P \cdot RiC(aX^2 + вX) \geq 1{,}1X \cdot P_F \qquad (64)$$

In this case, the permissible price for fertilizers is defined as

$$P_F \leq 0{,}82C_P \cdot RiC(aX + b), \text{ UAH/c a.i.} \qquad (65)$$

In our opinion, in this case, it is advisable to estimate the price of fertilizers for each crop in the crop rotation as acceptable according to the break-even criterion. The results of such determinations are shown in Table 66.

Table 66

Permissible (maximum) prices for products of certain crops

(for straw harvesting)

Crop	Fertilizer rate (X), c a.i./ha	Accepted intensity level of the variety (RiC)	Model parameters		Product price (C_P), UAH/c	Additional price of fertilizers (P_F), UAH/c a.i.
			a	b		
Winter wheat	2,42	1,50	–0,98	8,26	180 200 220	1303 1448 1593
Peas	2,56	1,20	–0,72	5,28	220 240 260	744 811 879
Spring barley	1,40	1,20	–0,58	5,09	160 180 200	674 758 842
Corn for grain	1,57	1,50	–0,97	9,27	100 120 140	779 935 1091
Sunflower	0,92	1,20	–0,45	3,92	700 800 900	2415 2760 3105

The data show significant differences between different crops up to the maximum possible fertilizer price. In the range of these product prices and at the current price of fertilizers, for example, 1200 UAH/ton per year, it is economically feasible to use them only for winter wheat and sunflower. However, such definitions are clearly insufficient as they are used to estimate a particular crop rotation and, consequently, the price of fertilizers in that crop rotation. It can be stated unequivocally that the larger the area under wheat and sunflower in a crop rotation, the more efficient the use of mineral fertilizers in the crop rotation will be. Table 67 shows calculations of the assumed price of fertilizers for each crop rotation at the assumed product prices.

Table 67

Establishment of a permissible price for mineral fertilizers for different crop rotations (when straw is planted)

Indicator	Crops					Total
	winter wheat	peas	spring barley	corn for grain	sunflower	
Product price (CP), UAH/c	200	240	180	120	800	–
Price of fertilizers (*PF*), UAH/c a. i.	1448	811	758	935	2760	–
Share of crops in 1 ha of agricultural land	0,29	0,14	0,14	0,29	0,14	1,0
The required amount of fertilizer, in a.i.	0,702	0,358	0,196	0,455	0,129	1,860
Cost of fertilizers, UAH	1016	290	149	425	356	2236
Assumed price of fertilizers in crop rotation, UAH/ton per year.	–	–	–	–	–	1202
Share of crops in 1 ha of agricultural land	0,25	0,25	0,25	0,25	–	1,0
The required amount of fertilizer, c a.i.	0,605	0,640	0,350	0,392	–	1,987
Cost of fertilizers, UAH	876	519	265	367	–	2027
Assumed price of fertilizers in crop rotation, UAH/ c a.i.	–	–	–	–	–	1020
Share of crops in 1 ha of agricultural land	–	0,25	0,25	0,50	–	1,0
The required amount of fertilizer, c a.i.	–	0,640	0,350	0,784	–	1,774
Cost of fertilizers, UAH	–	519	265	734	–	1518
Assumed price of fertilizers in crop rotation, UAH/ c a.i.	–	–	–	–	–	856

The data obtained show that, depending on the crop rotation, the permissible price of mineral fertilizers ranges from 1202 to 856 UAH/ton per a.i. Therefore, if the current (market) price of mineral fertilizers is, for example, 1200 UAH/ton per a.i., their effectiveness should be expected only in the first crop rotation. The most unprofitable use of fertilizers will be in the third crop rotation, since fertilizers should not be more expensive than 856 UAH/ton per a.i. for this crop rotation.

All of the above definitions and calculations allow us to formulate a number of basic and important, in our opinion, provisions:

1. From the point of view of economic evaluation, in all variants of fertilization (without fertilization, with 1 c a.i./ha and at a deficit-free rate), the problem is to choose a crop rotation in which

- the yield of grain units per 1 ha of crop rotation area and the cost of production is maximized (in case of discrepancy between these indicators, the choice is made according to one of them according to the customer's conditions);
- the permissible price for mineral fertilizers is not less than the existing price on the fertilizer market (in case of an inverse ratio, one of the solutions is the need for state support for the producer for the difference in prices).

2. From the point of view of environmental assessment, the problem is to establish a fertilizer rate that is not deficient in the main elements and then compensate for a possible humus deficit by sowing green manure crops in intermediate crops. It is worth noting the following:

- any alienation of by-products requires an increase in the area under these crops;
- the sowing area itself should not exceed the area of crops after which this sowing is possible, and in no way exceed the area of crop rotation.

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