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Optimization of Agricultural Enterprises' Sown Areas Considering Crop Rotation

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Abstract: This article explores contemporary scientific approaches to improving the efficiency of agricultural operations in Ukraine. It has been identified that insufficient attention has been given to optimizing the activities of agricultural enterprises. A model for optimizing crop areas, considering crop rotations in crop production or mixed-type enterprises, has been developed to ensure an increase in crop yields. The model incorporates factors such as soil health, pest management, and the economic feasibility of different cropping systems. By applying crop rotation principles, the model aims to achieve a balanced and sustainable agricultural practice, promoting both productivity and environmental sustainability. The findings highlight the importance of considering ecological factors and economic optimization in agricultural planning. The model demonstrates how the rotation of crops can prevent soil depletion and improve overall land use efficiency, thereby boosting the agricultural output of enterprises. The proposed approach is distinguished by its uniqueness, as it leverages advanced economic–mathematical methodologies and state-of-the-art information–analytical tools to enable the automation of the crop rotation planning process. The implementation of this approach can lead to more sustainable farming practices, enhanced soil fertility, and increased profitability.

Keywords: cropland optimization; crop rotation; agricultural enterprises; food security; yield improvement; agricultural economy

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1. Introduction

Agriculture is a vital component of Ukraine's agro-industrial complex and plays a crucial role in ensuring the nation's food security. The state of agriculture, firstly, determines the demand for production resources, thus stimulating the development of agricultural machinery manufacturing, agrochemical production, and material–technical services within the sector. Secondly, agricultural products, particularly those from crop and livestock production, serve as raw materials for the food industry and directly influence the availability of high-quality food products for the population, fulfilling their natural requirements for proteins, fats, and carbohydrates of both plant and animal origin.

However, an analysis of the dynamics of gross added value at current prices during 2015–2019 reveals that the annual growth rate in agriculture was only +8.3%, compared to an overall economic growth rate of +15.1%. This indicates that the agricultural sector's development has lagged significantly behind overall economic progress in recent years. These trends have resulted in the share of agricultural products in the national GDP decreasing from 14.2% to 10.5% during the same period.

Such negative trends underline the importance and timeliness of scientific research in this field, particularly in optimizing cropland allocation to support sustainable agricultural development.

Considering the high practical significance, social focus on ensuring national food security, and unresolved issues in economic development, domestic researchers have dedicated numerous works to studying ways to improve the efficiency of agriculture in Ukraine. An analysis of their recent works has allowed us to identify several key directions in scientific thought:

- Current economic state of the industry and prospects for further agricultural development in Ukraine have been studied by researchers such as I. Bozhidai, I. Burachek, M. Denysenko, V. Koshelnyk, N. Mykhailenko, D. Novikov, O. Potapov, and others [1–5]. These authors emphasize the slow pace of positive changes in the industry while noting the existing resource potential for rapid, intensive development.
- The acknowledgment of unsatisfactory rates of economic growth in the sector has necessitated the analysis of organizational and economic features of agricultural entities and the formation of sustainable competitive advantages in crop and livestock production. Key contributors in this area include V. Ivanchenko, M. Ihnatenko, T. Kostyuk, L. Levaieva, L. Marmul, N. Patyka, V. Tkachuk, and others [6–9]. These researchers argue that the competitiveness of agricultural products should be the main priority for the development of farms and agricultural enterprises, especially in the context of trade liberalization.
- The systemic lack of internal and external funding sources for agricultural operations has been highlighted in the works of V. Holian, Yu. Zastavnyi, K. Zakhozhai, O. Ilchuk, I. Kravchenko, and M. Slynko [10–13]. These researchers emphasize the importance of creating effective mechanisms for state support of agriculture. A significant drawback of this approach is the past experience of command–administrative management, where government protectionist policies for certain economic sectors often led to the irreversible loss of competitive advantages. However, state support for agricultural producers is a widely recognized practice globally, including in the European Union. Under the EU's Common Agricultural Policy, an effective two-tier subsidy system is in place, which constitutes a major expenditure in the EU budget. The primary goal of this policy is to encourage farmers, guarantee a minimum income, and support agricultural activities in unfavorable natural conditions. Thus, underestimating the role of the state in Ukraine's agricultural development places domestic producers of crops and livestock at a disadvantage, making them unable to compete with imported alternatives in terms of cost.
- The limited availability of state resources to support the agricultural sector fully has driven researchers to explore alternative sources of funding for the industry. One such direction in scientific thought is investment-driven innovation in agriculture. Contributions in this area include the works of L. Budnyak, L. Dorohan-Pysarenko, O. Yehorova, O. Zakharchuk, N. Koziar, I. Konovalova, L. Kustrych, V. Lavruk, Yu. Lupenko, D. Okara, I. Panchenko, N. Patyka, V. Chernyshov, and others [14–20]. These studies argue that technological lag can only be addressed by broadly implementing innovative strategies in the operations of agricultural enterprises. Mechanisms for achieving this include direct foreign and domestic investments. However, there is no consensus in society regarding the benefits of increasing foreign direct investment in the agricultural sector. Farmland is traditionally viewed as Ukraine's primary resource and competitive advantage in global markets, which fundamentally limits the volume of foreign investments. Conversely, domestic investments in any economic sector are typically channeled through the stock market, which in recent years has primarily served the needs of the state budget through government bond placements.

Certain scientific works focus on other aspects of the sector's operations, such as risk management or the role of social capital. Researchers like M. Hrytsaienko, A. Diuk, V. Ishchenko, and M. Kravets [21–23] have contributed to this direction.

In summarizing recent research, it is evident that most studies focus on improving the overall efficiency of the sector and ensuring its sustainable growth. However, insufficient attention has been given to optimizing the activities of agricultural enterprises and farms.

The importance of addressing these challenges at this stage is justified by understanding that the revival of the sector is impossible without qualitative changes in business practices aimed at improving the economic condition of entities in both the short- and long-term perspectives. Considering the low level of investment activity, agricultural enterprises should primarily rely on their own resources and internal funding sources.The aim of this article is to enhance the efficient use of agricultural lands by optimizing cropland allocation in crop farming or mixed-type enterprises, taking into account crop rotations and increasing crop yields.

The necessity of the crop rotation optimization model proposed in this study arises from a set of critical deficiencies and limitations characteristic of existing research. These shortcomings not only hinder the effective management of agricultural enterprises but also constrain the sector's overall efficiency and sustainability. The key issues identified are as follows:

1. Predominant focus on the macroeconomic state of the agricultural sector. A substantial body of scholarly work is dedicated to examining the general economic landscape of agriculture, encompassing its developmental prospects, the competitiveness of agricultural products, and the financial mechanisms designed to support the industry. While such studies provide valuable insights into overarching economic trends, they fail to offer precise, practical methodologies for optimizing resource allocation and enhancing operational efficiency at the level of individual agricultural enterprises. The absence of targeted approaches leaves a critical gap in addressing the microeconomic challenges that farms face in their daily operations.
2. Lack of emphasis on internal production optimization. A systematic deficiency has been identified in research that prioritizes the optimization of production processes directly within agricultural enterprises using advanced economic–mathematical modeling frameworks. Despite the growing recognition of the pivotal role of technological innovations and investment in agriculture, the specific mechanisms and methodological foundations necessary for their effective implementation remain underdeveloped. Existing studies frequently underscore the importance of modernization but do not provide comprehensive models or analytical tools that enterprises can employ to structure their production processes more efficiently.
3. Insufficient research on crop rotation management and its direct correlation with yield dynamics. The rational planning of crop rotations constitutes one of the fundamental determinants of long-term productivity and the economic viability of agricultural enterprises. Nevertheless, the existing body of literature does not offer sufficiently detailed models that would allow farms to systematically optimize their crop structure by taking into account both economic imperatives and agro-environmental constraints. Given the complex interplay between soil fertility, crop sequencing, and market demands, the absence of sophisticated decision-support models presents a significant challenge for modern agribusiness.

In light of these identified gaps, the crop rotation optimization model proposed in this study is intended to serve as a robust analytical tool that effectively addresses the outlined deficiencies. By integrating contemporary economic–mathematical methodologies with state-of-the-art information and analytical systems, this model aims to equip agricul-

tural enterprises with a scientifically grounded, systematically structured, and practically applicable framework for enhancing operational efficiency. In doing so, it contributes to the long-term sustainability and competitiveness of agricultural production, ensuring that farms can make informed, data-driven decisions that optimize both productivity and profitability.

2. Materials and Methods

The ratification of the Association Agreement between Ukraine and the European Union on 16 September 2014, and the establishment of a free trade area had significant economic implications for agriculture. Domestic producers gained duty-free access to the European market, which opened opportunities for export growth and improved the export structure by reducing the share of raw material components. At the same time, increased competition in the domestic market due to rising imports benefited end consumers and encouraged domestic agricultural producers to accelerate the adoption of modern technologies in crop and livestock farming. However, those producers unwilling to adapt to the demands of a purely competitive market were forced to scale down their activities, as their products would fail to meet the quality and price standards of their imported counterparts. Additionally, the high quality and safety standards for food products in EU countries necessitated compliance by domestic enterprises.

Transformational changes during the transition to an open economy are inevitable and often met with societal resistance. Nevertheless, they are essential for revitalizing the competitiveness of any economic sector, including agriculture.

An evaluation of key trends in crop production from 2015 to 2023 reveals steady growth in sown areas in Ukraine, as presented in Figure 1. These increased from 22,053 thousand hectares in 2015 to 24,804 thousand hectares in 2021, reflecting an average annual growth rate of +1.98%. Grain and leguminous crops dominated, accounting for 64% to 67% of total sown areas, followed by sunflower, whose share increased from 23.1% in 2015 to 26.7% in 2021. The further significant reduction in sown areas to 18,249 thousand hectares in 2023 was driven by geopolitical rather than economic factors.

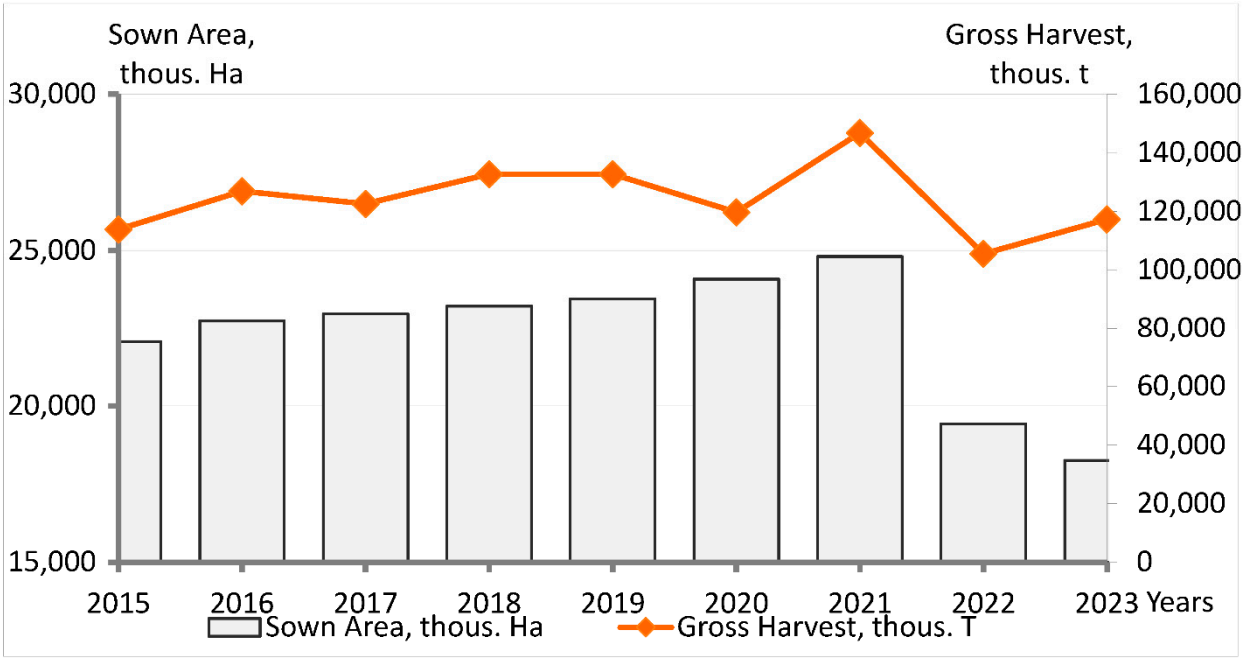

Figure 1. Dynamics of sown areas and gross harvest of agricultural crops, 2015–2023.

It is also worth noting that Ukraine's total agricultural land area is approximately 41 million hectares, of which 42–43% lay fallow annually. Given that the recommended crop rotation cycle for sunflower is 7–8 years in forest steppe regions and up to 9 years in steppe regions, the current share of sunflower cultivation limits the potential for further expansion of its sown area. Any attempt to increase its cultivation further would disrupt crop rotation schedules and lead to a decline in the fertility of agricultural lands.

Another significant characteristic of crop production during this period was the substantial decline in gross harvest, from 132.678 million tons in 2019 to 119.708 million tons in 2020. This decrease was attributed to unfavorable weather conditions and the overall slowdown in economic growth across the country. The most affected crops included sunflower, with production dropping by −14.1%; grains and legumes, declining by −13.6%; and sugar beet, which fell by −10.3%.

As a result, the average yield decreased from 56.6 centners per hectare (c/ha) in 2019 to 49.7 c/ha in 2020, marking the lowest level in recent years. In the period 2015–2019, yields had consistently increased from 51.6 c/ha to 56.6 c/ha. However, favorable weather conditions in 2021 enabled a 22.6% year-on-year increase in the gross agricultural output. The subsequent decline in the sector is directly linked to Russian aggression. To maintain high yields and prevent soil depletion, Ukrainian agriculture increasingly relies on the application of mineral and organic fertilizers. Notably, the use of mineral fertilizers has been growing rapidly. According to statistical data, the total volume of mineral fertilizers applied rose from 1.415 million tons in 2015 to 2.7797 million tons in 2020, reflecting an average annual growth rate of +14.5%. During the same period, the share of land treated with mineral fertilizers increased from 34.9% to 39.5%. Consequently, the volume of fertilizers applied per hectare of land doubled, from 34.1 kg in 2015 to 67.0 kg in 2020. The use of organic fertilizers, on the other hand, grew at a much slower pace, increasing from 9.663 million tons in 2015 to 11.414 million tons in 2020, with an average annual growth rate of +3.4%. Given that the application rates for organic fertilizers are significantly higher than for mineral fertilizers, the share of land treated with organic fertilizers expanded only marginally, from 1.0% in 2015 to 2.4% in 2020.

It is important to recognize that while fertilizers enhance soil fertility, they do not protect crops from diseases, pests, and weeds. In fact, improved fertilization and irrigation can exacerbate these problems by creating favorable conditions for their proliferation. Consequently, crop rotation plays an increasingly critical role in modern agriculture.

According to the definition provided in [23–25], crop rotation refers to the systematic alternation of agricultural crops and fallow periods over time within a defined area, following scientifically established norms of periodicity and taking into account the biological interactions between crops and their effects on soil fertility.

The prolonged absence of crop rotation leads to unbalanced and uneven depletion of soil nutrients, accumulation of toxic substances—byproducts of plant life—and increased prevalence of pathogens and pests. These factors negatively impact not only crop yields but also the quality of the harvested produce.

Considering the aforementioned factors, the methodological foundation of this study is based on statistical methods, particularly time series analysis, economic–mathematical modeling, and information technologies. The pursuit of maximum short-term profits by farming enterprises—driven by the incomplete land reform in Ukraine, internal economic instability, and external geopolitical uncertainty—does not always incentivize the implementation of planned crop rotation strategies. This underscores the pressing need for the optimization of sown areas while adhering to a recommended crop rotation plan that ensures the highest possible weighted average yield, taking into account the specialization of agricultural enterprises. Addressing this issue requires the development of an appropriate

economic–mathematical model, whose optimization will be carried out using advanced information–analytical tools. The proposed model is grounded in the methodological recommendations of the Ministry of Agrarian Policy of Ukraine regarding the recommended distribution of crops within crop rotations across various soil–climatic zones, as stipulated in the relevant regulatory directive [25].

3. Results

The decision-making process in the proposed model is appropriately represented in the form of the following diagram, Figure 2.

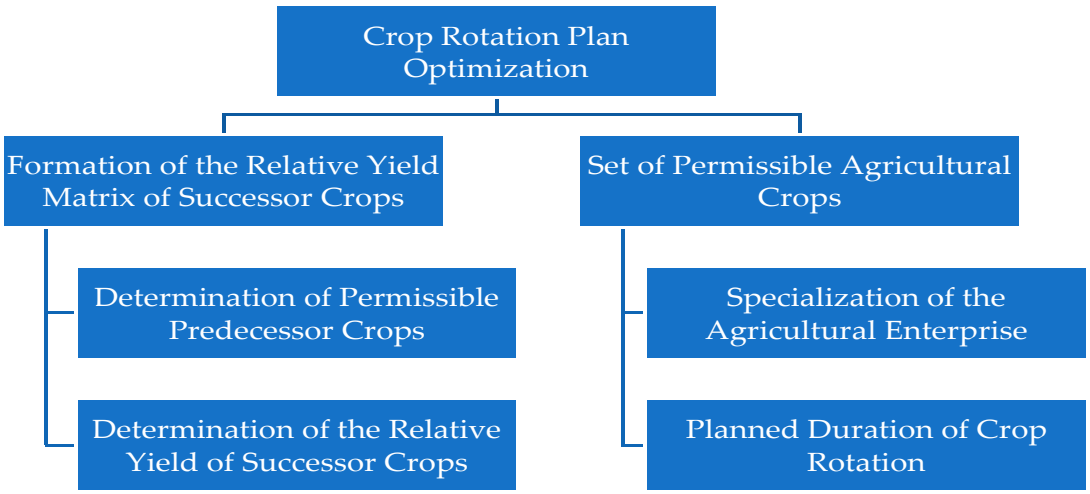

Figure 2. Stages of the decision-making process in the crop rotation planning optimization model.

The process of crop rotation planning is based on an optimization model designed to maximize the relative yield level. The input parameters of this model include a matrix of relative yields of successive crops and a set of permissible agricultural crops. The latter takes into account the specialization of the agricultural enterprise and the planned duration of the crop rotation cycle. Below, we provide a detailed economic and mathematical formulation of the problem.

Given the practical significance of this issue and the existing methodological advancements, this work develops a model to enhance the efficiency of agricultural land use by optimizing sown areas in crop production or in mixed-type enterprises while considering crop rotation. To this end, we introduce the following notation. Let the permissible set of agricultural crops consist of the following plant types:

I—winter wheat;
II—winter rye;
III—barley;
IV—oats;
V—corn for silage;
VI—corn for grain;
VII—peas;
VIII—soybeans;
IX—sugar beets;
X—early potatoes;
XI—late potatoes;
XII—sunflower;
XIII—perennial legume grasses;
XIV—annual grasses.

The justification for selecting this particular nomenclature of crop production is based on several objective reasons. As is well known, the fundamental requirements for any statistical information include completeness, relevance, reliability, and open access. It is evident that the primary source for aggregating such information at the industry level should be governmental statistical reporting bodies [24]. Secondly, the optimal ratio of agricultural crops in crop rotations across different soil and climatic zones is also regulated at the legislative level [25]. Therefore, the choice of the generalized nomenclature of crop production in this study is based on these sources, which already operate with this classification. According to [26], for each type of crop listed above, Table 1 outlines the optimal, permissible, and impermissible predecessor and successor crops.

Table 1. Permissible agricultural predecessor crops.

Crop (Predecessor)														Crop (Successor)
XIV	**XIII**	**XII**	**XI**	**X**	**IX**	**VIII**	**VII**	**VI**	**V**	**IV**	**III**	**II**	**I**	
x	x	н	yd	x	н	x	x	н	d	d	н	н	н	I
x	x	н	yd	x	н	x	x	н	d	н	yd	н	н	II
x	x	yd	x	x	x	x	x	x	x	yd	н	d	d	III
x	x	yd	x	x	x	x	x	x	x	н	yd	d	d	IV
x	x	yd	x	x	yd	x	x	yd	yd	x	x	x	x	V
x	x	yd	x	x	yd	x	x	yd	yd	x	x	x	x	VI
yd	н	d	x	x	x	н	н	x	x	x	x	x	x	VII
yd	н	d	x	x	x	н	н	x	x	x	x	x	x	VIII
d	d	н	d	d	н	d	d	yd	yd	d	d	x	x	IX
x	x	н	н	н	x	x	x	d	d	d	d	x	x	X
x	x	н	н	н	x	x	x	d	d	d	d	x	x	XI
x	н	н	x	x	yd	x	x	yd	x	x	x	x	x	XII
x	x	x	x	x	x	н	н	x	x	x	x	x	x	XIII
x	x	x	x	x	x	x	x	x	x	x	x	x	x	XIV

In Table 1, the following designations are used:

"x"—The best predecessor crop, after which the successor crop achieves the maximum possible yield, considering existing natural and agronomic conditions.

"d"—An acceptable predecessor crop that reduces the yield of the subsequent crop by more than 10%, assuming favorable natural and climatic conditions. In less favorable conditions, further yield reductions are possible.

"yd"—A conditionally acceptable predecessor crop significantly worsens the efficiency of cultivating the subsequent crop, reducing its yield by more than 50%. Such a crop rotation plan is not recommended.

"н"—An unacceptable predecessor crop that creates adverse water and nutrient conditions in agricultural lands for cultivating the subsequent crop.

Based on the data in Table 1 and the economic meaning of the designations, a matrix A[n*n] of relative yields is constructed, where n is the total number of crops that can participate in crop rotation, $n = 14$. The elements of matrix A take the following values:

$a_{i,j} = 1$, if the i-th predecessor is the best for the j-th successor;

$a_{i,j} = 0.85$, if the i-th predecessor is acceptable for the j-th successor;

$a_{i,j} = 0.45$, if the i-th predecessor is conditionally acceptable for the j-th successor;

$a_{i,j} = 0$, if the i-th predecessor is unacceptable for the j-th successor.

Thus, each $a_{i,j}$ indicates the relative yield level of the j-th crop following the i-th predecessor.

When planning crop rotation, it is also necessary to consider the periodicity of crop alternation, which depends on the natural zone and is provided in Table 2.

Table 2. Periodicity of crop rotation in agriculture (in years).

Steppe		Forest Steppe		Polissya		Plant Types
To	**From**	**To**	**From**	**To**	**From**	
3	1	3	2	3	2	I
2	1	2	1	2	1	II
2	1	2	1	2	1	III
2	1	2	1	2	1	IV
1	1	1	1	1	1	V
1	1	1	1	1	1	VI
4	3	4	3	4	3	VII
4	3	4	3	4	3	VIII
4	3	4	3	4	3	IX
2	1	3	2	3	2	X
2	1	3	2	3	2	XI
9	7	8	7	–	–	XII
4	3	4	3	4	3	XIII
4	3	4	3	4	3	XIV

In practical calculations, we will base the assumption on the longest rotation period typical for the southeastern part of Ukraine, i.e., the steppe region.

The decision-maker determines the maximum possible duration of the crop rotation, C_{max}, which needs to be planned. Then, the crops that will participate in the sowing plan are those defined by matrix D, whose elements are calculated using Formula (1).

$$d_i = \begin{Bmatrix} 1, & \text{if} \quad c_i \le C_{max} \\ 0, & \text{if} \quad c_i > C_{max} \end{Bmatrix}, \text{ for all } i = 1 \ldots n, \tag{1}$$

If $d_i = 1$, the rotation period for the i-th crop does not exceed the maximum allowable duration, C_{max}, and thus, it can be included in the plan, and vice versa.

The variables of the model being considered are the matrix of optimal crop rotation X[n*n], where the elements x_{ij} can take integer values of 0 or 1. If $x_{ij} = 1$, it means that the j-th crop should be the successor of the i-th predecessor.

To exclude from consideration those crops whose rotation period exceeds the allowable level, we introduce the following constraint:

$$\sum_{j=1}^{n} x_{ij} \le d, \text{ for all } i = 1 \ldots n, \tag{2}$$

Constraint (2) also automatically ensures that each crop included in the optimal crop rotation plan will participate only once.

If any agricultural enterprise specializes in crop production or is involved in animal husbandry and feed crop cultivation, it is necessary to ensure the presence of certain crops

in the optimal solution. To this end, constraint (3) should be added to the model for each type of plant.

$$\sum_{j=1}^{n} x_{ij} = 1, \tag{3}$$

It is also necessary to ensure that every grown crop, which is a successor to any first crop, should also be a predecessor to the second crop. Simultaneously, the proposed solution should ensure the cyclic change of crops through C_{max} or a smaller number of years. These conditions are achieved through the system of constraints (4):

$$\left\{ \begin{array}{c} \sum_{i=1}^{n} x_{i1} = \sum_{j=1}^{n} x_{1j} \\ \sum_{i=1}^{n} x_{i2} = \sum_{j=1}^{n} x_{2j} \\ \ldots \\ \sum_{i=1}^{n} x_{in} = \sum_{j=1}^{n} x_{nj} \end{array} \right\}, \tag{4}$$

For example, in the first equation of system (4), the sum on the left in the first column can take values of 0 or 1. This means that the first crop is either not a successor to any other crop or is a successor to another crop. The sum on the right-hand side of the equation in the first row should also take values of 0 or 1. That is, the same first crop is either not a predecessor to the next crop or is a predecessor to the next crop. Similar identities should be taken into account for each type of plant.

The constraint on the crop rotation period with the desired duration in years can be written as follows (5):

$$\left(T = \sum_{i=1}^{n} \sum_{j=1}^{n} x_{ij} \right) \leq C, \text{ for all } i, j = 1 \ldots n, \tag{5}$$

Inequality (5) should be replaced with an equality of the period T.

T is always required to equal the expert-chosen parameter C_{max}. To mitigate risks in agricultural activities associated with unstable weather conditions, as well as to ensure a diverse range of crop products and maintain a stable level of profitability each year, the enterprise divides the available land area into T.

T equals parts and adheres to the selected crop rotation plan, cultivating crops simultaneously. The final component of the model is the objective Function (6), which, in our case, maximizes the relative yield level of the entire agricultural area:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_{ij} \rightarrow \max, \tag{6}$$

If the farming enterprise has data on the forecasted price levels for crop production and planned costs for its cultivation, then the considered objective function can be modified to find the maximum possible expected profit. The use of permissible or conditionally permissible successors will worsen this indicator. Summarizing the above, the optimization model for crop acreage in crop production or mixed-type enterprises, taking crop rotation into account, will take the following form (7):

$$\begin{array}{c} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_{ij} \rightarrow \max, \\ 0 \leq x_{ij} \leq 1, \quad x_{ij} \in Z, \quad i, j = 1 \ldots n \end{array} \tag{7}$$

where K is the set of agricultural crops that must be grown due to the enterprise's specialization.

Next, we will conduct a practical trial of the developed model with different input data. In the first case, assume that the enterprise specializes in growing winter wheat and rye. From the data in Table 1, it is evident that both crops are unacceptable predecessors to each other. Therefore, the optimal crop rotation schedule should involve growing other

crops between them. It should also be taken into account that the rotation period for wheat in the steppe is up to three years, and for rye, it is up to two years. Considering this, the value of Cmax should not be selected as less than 4. Otherwise, this would violate the recommended sequence for growing the crops. The optimization of model (7) was performed using the "Solver" tool in Excel spreadsheets. The corresponding results for the crop rotation schedule for winter wheat and rye, represented by matrix X, are shown in Table 3.

Table 3. Crop rotation schedule for growing winter wheat and rye.

Plant Types (Successor)														Plant Types (Predecessor)
XIV	XIII	XII	XI	X	IX	VIII	VII	VI	V	IV	III	II	I	
0	0	0	0	0	0	0	1	0	0	0	0	0	0	I
0	0	0	0	1	0	0	0	0	0	0	0	0	0	II
0	0	0	0	0	0	0	0	0	0	0	0	0	0	III
0	0	0	0	0	0	0	0	0	0	0	0	0	0	IV
0	0	0	0	0	0	0	0	0	0	0	0	0	0	V
0	0	0	0	0	0	0	0	0	0	0	0	0	0	VI
0	0	0	0	0	0	0	0	0	0	0	0	1	0	VII
0	0	0	0	0	0	0	0	0	0	0	0	0	0	VIII
0	0	0	0	0	0	0	0	0	0	0	0	0	0	IX
0	0	0	0	0	0	0	0	0	0	0	0	0	1	X
0	0	0	0	0	0	0	0	0	0	0	0	0	0	XI
0	0	0	0	0	0	0	0	0	0	0	0	0	0	XII
0	0	0	0	0	0	0	0	0	0	0	0	0	0	XIII
0	0	0	0	0	0	0	0	0	0	0	0	0	0	XIV

Thus, the sequence of plantings, based on the obtained solution, is determined as follows:

After winter wheat (I), it is proposed to grow peas (VII) since the element $x_{17} = 1$

Next, we focus on the successor of peas, which is winter rye (II) because $x_{72} = 1$

The successor of rye is early potatoes (X), corresponding to $x_{2,10} = 1$

Finally, the successor of potatoes is again winter wheat since $x_{10,1} = 1$

The specified process is graphically represented in Figure 3.

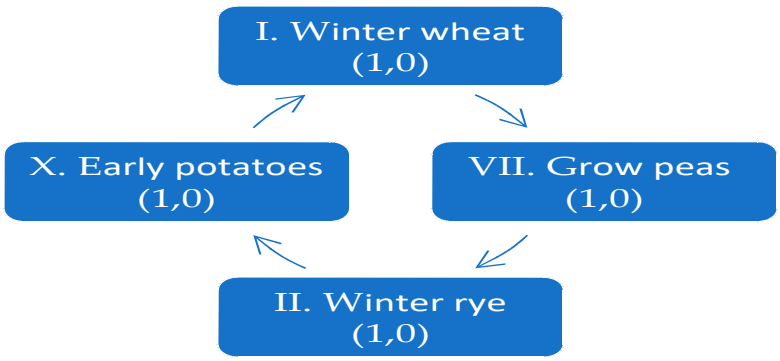

Figure 3. Stages of crop rotation based on optimization results.

In Figure 3, the relative yield level of successive crops is indicated in parentheses at each stage of the crop rotation. As observed, the proposed plan ensures the presence of the most favorable predecessor crops, after which the successive crops achieve the highest possible yield levels, considering the existing natural and agronomic conditions.

As we can see, the proposed crop rotation scheme is cyclical, which corresponds to the economic meaning of the task. However, this solution is not unique. Suppose that the production plans of this agricultural enterprise do not involve growing peas. In this case, the following restriction should be added to the set of constraints in our problem:

After conducting the next optimization of the objective function, we obtained the following recommended planting sequence: winter wheat, early potatoes, winter rye, annual grasses, and so on. Thus, by determining the desired assortment of agricultural products by adding constraints to the model and adjusting the input parameter Cmax, we will obtain the crop rotation scheme as the output.

The presented economic–mathematical model (7) is universal and, with appropriate adjustments, can be applied to optimize crop rotation plans not only in Ukrainian crop production. Depending on the specifics of agricultural land and climate conditions in different regions, modifications may be required for the relative yield levels defined by matrix A and the periodicity of crop rotation, as shown in Table 2. Regarding Ukraine, the specified data were obtained from the methodological recommendations of the Ministry of Agrarian Policy of Ukraine. For other countries, such data can be derived from agricultural practices in those regions and may serve as a foundation for further research.

4. Conclusions

As a result of the research into current trends in scientific thought regarding the improvement of agricultural efficiency in Ukraine, it was found that in recent years, insufficient attention has been given to optimizing the activities of economic entities. An analysis of the dynamics of key indicators in crop production showed a significant decline in the average crop yield on agricultural lands in 2020, as well as a planned increase in the use of mineral and organic fertilizers to prevent this. At the same time, one of the most effective mechanisms for improving soil fertility and protecting crops from diseases and pests is crop rotation. In this context, the scientific novelty of this work lies in the development of a model for optimizing the planting areas of agricultural enterprises, taking into account crop rotation based on methodological recommendations regarding the ratio of agricultural crops in different soil–climatic zones of Ukraine. Unlike existing models, this approach relies on modern economic–mathematical tools and allows the automation of this process while considering the desired assortment of crop production. Statistical studies have shown that the existing structure of agricultural land use in Ukraine does not comply with the principles of rational natural resource management, as the crop rotation plan has not been implemented. Therefore, in further research, it is advisable to apply a scenario-based approach to assess the expected changes in crop specialization across different natural zones of Ukraine, considering this methodology. The universality of the proposed model, after appropriate adjustments to input parameters in accordance with agricultural practices in a given region, also allows its application in the activities of farm enterprises beyond Ukraine.

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