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Optimisation of crop rotations: A case study for corn growing practices in forest-steppe of Ukraine

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Abstract: The formation of optimal crop rotations is virtually unsolvable from the standpoint of the classical methodology of experimental research. Here, we deal with a mathematical model based on expert estimates of "predecessor-crop" pairs' efficiency created for the conditions of irrigation in the forest-steppe of Ukraine. Solving the problem of incorporating uncertainty assessments into this model, we present new models of crop rotations' economic efficiency taking into account irrigation, application of fertilisers, and the negative environmental effect of nitrogen fertilisers' introduction into the soil. For the considered models we pose an optimisation problem and present an algorithm for its solution that combines a gradient method and a genetic algorithm. Using the proposed mathematical tools, for several possible scenarios of water, fertilisers, and purchase price variability, the efficiency of growing corn as a monoculture in Ukraine is simulated. The proposed models show a reduction of the profitability of such a practice when the purchase price of corn decreases below 0.81 EUR·kg^{-1} and the price of irrigation water increases above 0.32 EUR·m^{-3} and propose more flexible crop rotations. Mathematical tools developed in the paper can form a basis for the creation of decision support systems that recommend optimal crop rotation variations to farmers and help to achieve sustainable, profitable, and ecologically safe agricultural production. However, future works on the actualisation of the values of its parameters need to be performed to increase the accuracy.

Keywords: combinatorial optimisation, corn, crop rotation, genetic algorithms

INTRODUCTION

An important aspect of sustainable development is the planning of agricultural production, which can serve as a stabilising factor of economic activities and anticipate a long-term impact on environmental processes [Romashchenko *et al.* 2017]. Such planning is grounded on the concept of crop rotation that is significant from biological, ecological, and particularly in the context of organic farming [Ostapenko *et al.* 2020]; economic and technological points of view [Gadzalo *et al.* 2015; Kaminsky, Boyko 2014a, 2014b; Kovalenko 2012; Nuppenau 2011; Romashchenko *et al.* 2016b; Schönhart *et al.* 2009; Yurkevich *et al.* 2011].

It should be noted that at present in Ukraine, as was observed and studied in other countries like Bangladesh, Sri Lanka, and the United States [Nuppenau 2011; Thrupp 2000], there is a trend to decrease the number of crops in crop rotations and to cultivate only the most profitable crops without taking crop rotations into account [Kaminsky, Boyko 2014a, 2014b]. On the one hand, in the case of the central US states, according to Plourde *et al.* [2013], the percentage of areas where corn is grown as a monoculture increased from ~3.5% to ~8% in the period of 2007–2010 compared to the period of 2003–2006. Reasons for this are primarily economic and political [Plourde *et al.* 2013]. On the other hand, in the case of Argentina, Cisneros *et al.* [2011] argue that the concept of monoculture is likely to be rejected by farmers.

Given such different trends, effective scenario planning of crop rotations on farms requires joint consideration of the impact of the maximal possible number of factors on the processes of crop growing and uncertainties that arise from variability in economic factors. Such planning is impossible without the wide use of mathematical modelling, which is one of the most effective methods for optimal selection of alternating crops in crop rotations [Detlefsen 2004; Dury *et al.* 2012; Garcia *et al.* 2005; Kovalenko 2007; Osman *et al.* 2015; Schönhart *et al.* 2009; Vergunova 2000].

Let us note that the problem of optimal crop rotation formation is, in general, virtually unsolvable from the standpoint of the classical methodology of experimental research due to a large number of influencing factors and possible solutions. Their consideration without taking the economic component into account is not relevant in the current conditions of the wide availability of means and technologies to compensate for the malnutrition of plants. This problem can be more urgent in organic farming compared to conventional approaches due to the higher cost of organic fertilisers [Ostapenko *et al.* 2020]. In this situation, assessments of crop rotations' economic efficiency are solely means of decision-making support for farmers that allow significant narrowing of the number of options for further development of their business, which, in any case, require further study and evaluation taking the particular situation into account.

In Ukraine, such support in decision-making is urgent while growing corn in the steppe and forest-steppe zones because the main limiting factor of corn productivity here is the unfavourable water regime of soils which hinders the realisation of agro-resource potential [Lavrynenko *et al.* 2009]. To obtain high and stable yields, the most effective method in these conditions is the use of irrigation in combination with fertigation. Yield increase obtained from the optimisation of water and nutrient regimes ranges from 110 to 380% compared to non-irrigated conditions [Lavrynenko *et al.* 2009], and the largest increase in crop productivity is achieved by drip irrigation. High fluctuations in agricultural means prices in Ukraine raise a need to construct decision-support tools for crop selection and allocation that consider such variability.

It should be noted that an important principle that is often taken into account when constructing crop rotation models is the consideration of crop rotation type's influence on crops' yield and the level of influence of the defined series of predecessors on crops' yield [Dury *et al.* 2012; Schönhart *et al.* 2009; Vergunova 2000]. As the criteria of crop rotation's optimality, such goal functions as achievement of the maximal value of net operating profit or gross output are considered in line with ecological restrictions imposed to preserve soil fertility [Dury *et al.* 2012; Osman *et al.* 2015].

Due to the complexity of processes occurring in cultivated crops, the main approach for constructing such models is the approach described in the works of Detlefsen [2004] and Schönhart *et al.* [2009], which is based on expert assessment [Garcia *et al.* 2005; Kovalenko 2007; Dury *et al.* 2012] of crop's growing efficiency depending on its predecessor. Note that this assessment method mainly considers the agronomic component of the process with little attention to economic factors. Their consideration while optimising crop rotations requires the use of crop yield models which take into account the conditions of the crop's growing, effects of fertilisation, and irrigation.

Regression models of corn yield under irrigation for the conditions of Ukraine are predominantly studied for the steppe zone [Glushko 2012; Khamukov, Malamatova 2004; Kokovykhin *et al.* 2011; Ushkarenko, Likhovid 2016]. Among the studies devoted to other climatic zones, the paper by Avramenko *et al.* [2012] should be mentioned. The peculiarity of these models that complicates their effective application for economic scenario modelling is that even describing the influence of both irrigation and fertilisation on crop yield, they mainly focus on the known schemes for the introduction of nutrients. Experimentally obtained models that describe the influence of deviations from biologically optimal fertiliser introduction schemes on yield (similarly, in particular, to Mackay and Eaves [1962]), which is economically important in the conditions of Ukraine, are, to the best of our knowledge, not yet constructed. Another important factor needed to be considered is the uncertainty in input data. For the conditions of Ukraine, this factor is studied, in particular, by Balchenko *et al.* [2014] using fuzzy logic tools, however, only in the context of growing one crop.

Thus, for the conditions of Ukraine, the unsolved problem on which the paper focused is the problem of creating such algorithms for decision support in the process of crop rotation formation that would take into account economic factors and initial data uncertainties.

In this context, this study aims to develop new algorithms for crop rotation optimisation, which would use the results of previous experimental studies, and apply them to simulate the effectiveness of corn cultivation practices in Ukraine, specifically corn growing as a monoculture under irrigation.

Trends in the development of agriculture in Ukraine under modern conditions are to the great extent connected with the problem of crop rotation optimisation regarding that climate change significantly impacts the zonal placement of crops. In Ukraine, four environmental zones are distinguished according to the type of landscape: steppe, forest-steppe, Polissya region, and Ukrainian Carpathians [Marinich *et al.* 1985; Romashchenko *et al.* 2015] (Fig. 1). Climate change, which in Ukraine is characterised by the European highest rates of average annual temperature increase, significantly impacts the conditions of crop growing in these zones. Given this fact, the growth of such crops as soybeans and corn became problematic in the steppe zone but favourable hydro-thermal conditions for it were formed in the zone of forest-steppe and Polissya.

In this regard, we choose the forest-steppe zone of Ukraine (Fig. 1) as the area for the conditions to which this study is primarily related. The climate in the forest-steppe zone is temperate continental. The average temperature in January is −4°C in the west and −8°C in the east. In July it is +16°C and +22°C, correspondingly [Marynych 1993]. The amount of precipitation varies from 500 to 600 mm [Marynych 1993], but almost the same amount of water evaporates meaning a sufficient level of moisture supply. In some years, droughts are observed, especially in the southern part of the area. The soil cover of the forest-stepe zone is dominated by various types of chernozem and grey forest

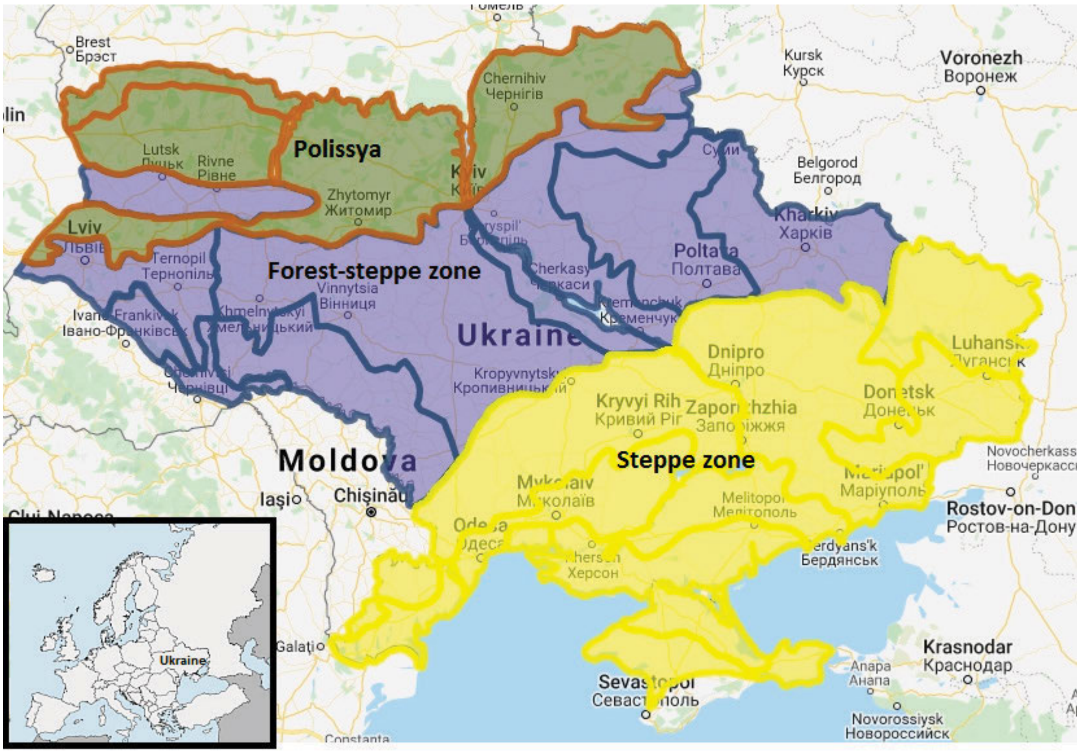

Fig. 1. Environmental zones of Ukraine; source: own elaboration based on BioModel [undated], Map of Europe [undated], Google Maps

soils formed on loess or loess-like loams [Marynych 1993]. The level of soil fertility is highest in the middle and eastern parts of the area.

While conducting farming in the considered area, in most cases, biologically substantiated crop rotations are ignored and their structure is determined by the demand for crops and the profitability of their growing. Saturation of crop rotations with highly profitable and, generally, hydrophilic crops (soybean, corn, and vegetables) with a high need for nutrients is observed [Kaminsky, Boyko 2014b]. As the share of fodder crops, especially leguminous grasses, and possibilities of organic fertilisers' application has declined dramatically due to the reduction of the livestock sector, farmers are switching to the predominant use of mineral fertilisers. Such practices conflict with the principle of ecologically balanced agricultural production and the issue of the application of biologically substantiated crop rotations become more and more urgent.

Among the crops that are often grown as a monoculture, we can single out corn, which, in general, is one of the most important grain crops in the agricultural sector of Ukraine. It accounts for [Lavrynenko *et al.* 2009] 13.1–17.5% of all arable land (4.15–5.45 mln ha) and 22–24% of export volumes of all groups of agricultural products. In Ukraine, the sown area of corn has been growing linearly for the last 25 years. The average yield of corn in recent years ranges from 5.0 to 7.7 Mg·ha^{-1} with a tendency to increase.

MATERIALS AND METHODS

We consider the problem of selecting optimal crop rotation taking into account economic and ecological factors [Romashchenko *et al.* 2021], assuming that:

- an agronomic expert assessment of the efficiency of crop growing depending on its predecessor is the percentage of the maximal yield of this crop that can be obtained in this situation [Manzhos, Shuljha 1998; Shevchenko, Manzhos 1998];
- under other optimal conditions, the variable part of expenses is the cost of fertilisation and irrigation;
- the negative ecological effect of fertilisation is proportional to the amount of nitrogen fertiliser deposited into the soil.

We consider the upper estimates of the profit (P , EUR) from growing a crop (c) with a purchase price (C_c , EUR·kg^{-1}) and yield (Y_c , kg·ha^{-1}), on a field with an area (A , ha), in such a form:

$$P(A,c) = A \cdot (C_c \cdot Y_c \cdot K_Y - C_{NPK}(N,P,K,c)) \quad (1)$$

or

$$P(A,c) = A \cdot (C_c \cdot Y_c \cdot K_Y - I_c \cdot C_w - C_{NPK}(N,P,K,c)) \quad (2)$$

where: K_Y = the expert assessment of the efficiency of a pair "predecessor-crop" that is interpreted as the coefficient of yield decrease, C_{NPK} (N,P,K,c) = the minimal price of the set of fertilisers that ensures the introduction of the needed amount of nutrients for c (EUR·ha^{-1}) , C_w = the price of irrigation water (EUR·m^{-3}), I_c = the volume of irrigation water (m^3·ha^{-1}).

In addition, we consider a model that takes into account only the revenue component:

$$P(A,c) = A \cdot C_c \cdot Y_c \cdot K_Y \quad (3)$$

We assume that the prices C , $C_{NPK}(N,P,K)$, and C_w are described by random variables with normal distribution, whose parameters can be obtained, in particular, by known algorithms from retrospective data. Mean and variance of the variable C will be further denoted as μ_C and $\sigma_C{}^2$.

In the case of the estimate (Eq. 1), the yield Y of a crop depends on the quantities of the nutrients (N,P,K) according to the balance model [LAZER, MIKHEIEV 2006]

$$\{N,P,K\}(Y) = $$
$$= \frac{Y \cdot V_{\{N,P,K\}} - A_{\{N,P,K\}} K_{s,\{N,P,K\}} - OA_{o,\{N,P,K\}} K_{o,\{N,P,K\}}}{K_{f,\{N,P,K\}}} \quad (4)$$

where: $V_{\{N,P,K\}}$ = the rates of nutrients (N, P, or K) removal from soil by a crop (kg·Mg^{-1}); $A_{\{N,P,K\}}$ = the nutrient contents in soil (kg·ha^{-1}); $K_{s,\{N,P,K\}}$, $K_{f,\{N,P,K\}}$ = the coefficients of nutrients usage from soil and fertilisers (%), O = the rate of organic fertiliser application (Mg·ha^{-1}); $A_{o,\{N,P,K\}}$ = the contents of nutrients in organic fertiliser (kg·Mg^{-1}); $K_{o,\{N,P,K\}}$ = the coefficients of nutrients usage from organic fertiliser (%).

The value of $C_{NPK}(N,P,K)$ is obtained [ROMASHCHENKO *et al.* 2016a] as the minimal price of the set of fertilisers retrieved from the database that provides the quantities of N,P,K nutrients calculated with Equation (4) for the fixed yield Y . The maximal profit is calculated maximising $P(A,c)$ by the choice of Y using the gradient method.

In the profit estimate (Eq. 2), we use yield models described in MATYASH [2009] that have the following form:

$$Y = Y_{\max} f_1(I) f_2(N,P,K) \quad (5)$$

where: $Y_{\max}$ = the yield of a crop under the optimal conditions; f_1, f_2 = functions that describe yield reduction caused by non-optimal irrigation and fertilisation regimes.

We choose the function f_1 according to MATYASH [2009] in such form:

$$f_1(\omega,\xi) = \begin{cases} 1,\ K > 1, \\ a_0 + a_1 K + a_2 K^2,\ K_o \le K \le\ 1, \\ b_0 + b_1 K + b_2 K^2,\ K \le K_o, \end{cases} \quad (6)$$

$$K = \begin{cases} \frac{u+\xi}{\omega+\xi}\ if\ u \le u_d \\ \frac{u_d+\xi}{\omega+\xi}\ if\ u > u_d \end{cases} \quad (7)$$

where: ω = the biologically optimal irrigation rate for a year of a given water availability, u = the actual irrigation rate, u_d = the designed irrigation rate for a year of given water availability.

Influence of imbalance in the introduction of nutrients on yield was modelled as follows:
- for the given parameters $\{N,P,K\}$ of the function f_2 , we find the yield (Y_{opt}) using Equation (4):

$$Y_{opt} = \min_{Y_{opt}} ||\{N,P,K\}(Y_{opt}) - \{N,P,K\}|| \quad (8)$$

- the function f_2 , in which we introduce a component that reduces a yield under the condition of the imbalance of nutrients application, takes such form:

$$f_2 = \frac{Y_{opt}}{Y_{\max}} - k||\{N,P,K\}(Y_{opt}) - \{N,P,K\}|| \quad (9)$$

where: k = the given constant.

The value $C_{NPK}(N,P,K)$ is computed as:

$$C_{NPK}(N,P,K) = C_N \cdot N + C_P \cdot P + C_K \cdot K \quad (10)$$

where $C\{N,P,K\}$ = the average costs of a unit of nutrients calculated using fertilisers database.

The maximal profit is calculated maximising $P(A,c)$ by the choice of N,P,K,I_c using the gradient method. Here, $C_{NPK}(N,P,K)$ is calculated by Equation (10). After obtaining the optimisation problem solution, the approximation of the optimal $P(A,c)$ is calculated by selecting a set of fertilisers for the values N,P,K found in the process of maximisation.

In the case of the farm that contains n fields with the areas A_i, $i = 1,\dots, n$, the estimate of the total expected profit within crop rotations consisting of m_i crops c_{ij}, $i = 1, \dots, m$ will be

$$P_F = \sum_{j=1}^{m} \sum_{i=1}^{n} P(A_i, c_{ij}) \quad (11)$$

where: $P(A_i,c_{ij})$ = calculated according to Equations (1), (2), or (3). It should be noted that $P(A_i,c_{ij})$ and, correspondingly, P_F are normally distributed random variables.

To take into account the negative influence of fertilisers introduction on the ecological state, we add the corresponding empirical component to Equation (11) obtaining:

$$P_F = \sum_{j=1}^{m} \sum_{i=1}^{n} \left(P(A_i, c_{ij}) - E_k \cdot N_{ij} \right) \quad (12)$$

where: E_k = the coefficient that simulates the negative impact from the introduction of nitrogen fertilisers on the ecological state, N_{ij} = the quantity of nitrogen fertiliser introduced on the field i during the year j.

As an acceptable level of risk we use the probability (p) that the value P_F will be outside the range $[\mu_{P_F} - \sqrt{2}\sigma_{P_F}\mathrm{inverf}(p), \mu_{P_F} + \sqrt{2}\sigma_{P_F}\mathrm{inverf}(p)]$, where inverf is the inverse error function and that directly follows from the well-known inversion of the normal distribution.

Then, the estimate of the minimal total profit at the given level of risk will be equal to:

$$P_{\min}(p) = \mu_{P_F} - \sqrt{2}\sigma_{P_F}\mathrm{inverf}(p). \quad (13)$$

We state the optimisation problem as follows: find the values of m_i and c_{ij}, $i = 1, \dots, m$ that maximise $P_{\min}$ for the given:
- up to three fixed crops to be included in crop rotations on each field;
- conditions of growth (climatic zone, type of soil and its granulometric composition);
- parameters: risk level (p), crop prices (C), water price (C_w), database of fertilisers available on the market that contains their composition and prices, coefficient (E_k).

Basically, the considered problem of optimal crop rotation selection is a problem of combinatorial optimisation. The exact numerical method that can be used to obtain its solution is the exhaustive search method [TREVISAN 2011], which is NP-complete. To reduce the complexity of finding the optimal crop rotation such approaches as formulation of the problem in the form of a linear programming problem [SCHÖNHART *et al.* 2009] and usage of the branch and bound [Alfandari *et al.* 2015; Santos *et al.* 2015] or heuristic methods [Lee *et al.* 2015; Pavón *et al.* 2009] are used. The latter approach is used, particularly, in the work by Pavón *et al.* [2009], to solve multicriterial problems that consider both economic and ecological criteria for assessing crop rotation.

We consider the problem in the situation when profit from growing a particular crop on one field is estimated by Equations (1), (2), or (3) in the general case, in the case of deterministic prices, and in the case of one field.

The considered problem is a problem of combinatorial optimisation, and the value of the goal function itself is calculated (except for the model based on Eq. 3) as a solution to the problem of convex optimisation with constraints. The latter is proposed to be solved by the gradient method with the pseudo-inversion operation that performs projection on the set of permissible solutions [Romashchenko *et al.* 2016a].

Thus, we perform the selection of optimal crop rotation by solving three embedded optimisation problems. At the upper level, the combinatorial problem of optimal selection of crop rotation with the goal function (Eq. 13) is solved. Calculation of the goal function value requires a solution to the problem of choosing the optimal yield level taking into account the price of a crop, the cost of fertilisers and irrigation water, and the negative ecological effects of the introduction of nitrogen fertilisers into the soil. This problem is solved by the gradient method with a numerical calculation of the goal function's derivative, the value of which itself is the solution to the problem of optimal selection of a set and a number of fertilisers that provide an introduction of the required quantity of nutrients into the soil.

Given the complexity of the goal function (Eq. 13) values calculation, the use of metaheuristic methods, in particular genetic algorithms [Goldberg 1989], is urgent to efficiently solve the considered combinatorial problem. Features of the proposed genetic algorithm, which allows for obtaining an approximate solution to the problem, are as follows:

- potential solutions are fixed-size crop rotations for each field of a farm;
- the procedure for performing a crossover operation consists of the following steps. Two potential solutions are chosen weighted randomly with the values of the goal function (Eq. 13) as weight coefficients. For each field, we copy the "predecessor-crop" pair from the crop rotation contained in the second of the selected potential solutions to a crop rotation, contained in the first one. The copied pairs are determined weighted randomly. Estimates of profit calculated upon Equations (1), (2), or (3) are used as weight coefficients;
- the mutation operation consists of random, with the given probability, change of the randomly selected crop in a crop rotation for each field in the potential solution generated by the crossover operation;
- one iteration of the algorithm consists of performing the crossover operation, after which the mutation operation is applied with the given probability. If the estimate (Eq. 13) of the generated potential solution is greater than the lowest estimate among the solutions contained in the population, the new solution replaces the solution in the population with the lowest value of the estimate;
- the iterative process completes when the maximal and the minimal profit estimates of the potential solutions contained in the population differ no more than by the given value.

Since the proposed genetic algorithm is an algorithm of random search, it can propose crop rotations with close values of the goal function but different compositions. To obtain a fixed solution, assuming that the genetic algorithm converges to solutions around one local maximum, we propose to additionally apply a certain number of iterations of the greedy search algorithm after the genetic algorithm's convergence.

RESULTS AND DISCUSSION

To test the proposed algorithm and its software implementation, the simulation of the situations of corn growing as a monoculture and in short crop rotations on sod-podzolic soils with sandy granulometric composition in the sub-zone of forest-steppe (Fig. 1) was conducted.

In the computational experiments, the purchase price for winter wheat was taken at the level of 0.18 EUR·kg^{-1}, and for potatoes – at the level of 0.26 EUR·kg^{-1}, the price of corn varied. The maximal seasonal irrigation rate for winter wheat was taken at the level of 2200 m^3·ha^{-1}, for potatoes – at the level of 3200 m^3·ha^{-1}, for corn – at the level of 3500 m^3·ha^{-1}. The range in which corn yield varies was 10–14 Mg·ha^{-1}, for winter wheat this range was equal to 5–9 Mg·ha^{-1}, and for potatoes – to 30–60 Mg·ha^{-1}. We considered the situation of the year of 50% water availability.

Growing corn as a monoculture is one of the best scenarios according to the used database of biological estimates. Efficiency in such a situation is 89%.

When performing simulations according to the model based on Equation (3) that does not take expenses into account, the cultivation of corn was proposed to be carried out in crop rotations of the form "corn – potato – sugar beet" (efficiency – 80%, maximum yield of potato – 60 Mg·ha^{-1}, of corn – 14 Mg·ha^{-1}, of sugar beet – 80 Mg·ha^{-1}, the purchase price of potato – 0.26 EUR·kg^{-1}, of sugar beet – 0.23 EUR·kg^{-1}, the purchase price of corn – 0.17 EUR·kg^{-1}). Purchase prices here and further were taken as an average value according to the website [Agro-Ukraine undated] for October–November 2020. Growing corn as a monoculture according to the model based on Equation (3) in such conditions is effective only at the purchase price of corn above 1.13 EUR·kg^{-1}, which is significantly higher than the current level of prices. The effective use of sugar beet in the proposed crop rotation and considered conditions is consistent with the results given by Hanhur *et al.* [2015]. The economic efficiency of potato growth in crop rotation with corn for soil conditions close to considered ones is confirmed in Vyshnevskii [1999].

Modelling the economic efficiency of corn cultivation taking into account the cost of fertiliser at the plough depth of 0.22 m according to the model based on Equation (1) for one field shows that its cultivation as a monoculture becomes effective only at the purchase price above 0.97 EUR·kg^{-1}. Simulated crop rotations for the purchase price equal to 0.97 EUR·kg^{-1} and the statistically possible for the year 2020 level of 0.17 EUR·kg^{-1} are given in Table 1 and 2. Here and further, N, P, K means the actual mass of the substance that will be removed from soil by plants and must be compensated by the application of mineral and organic fertilisers. The coefficients of the balance model (Eq. 4) were taken according to the data given by Senchuk [2017]. The rates of substances' utilisation from fertiliser were taken as equal to one. It

Table 1. Crop rotation obtained using the model based on Equation (1) for the price of corn equal to 0.97 EUR·kg^{-1}

Crop	Yield (Mg·ha^{-1})	N	P	K
		kg·ha^{-1}		
Year 1: corn	14	353	168	443
Year 2: corn	14	353	168	443
Year 3: corn	14	353	168	443

Source: own study

Table 2. Crop rotation obtained using the model based on Equation (1) for the price of corn equal to 0.17 EUR·kg^{-1}

Crop	Yield (Mg·ha^{-1})	N	P	K
		kg·ha^{-1}		
Year 1: corn	12	363	172	454
Year 2: potato	6	315	86	503
Year 3: potato	6	666	187	992

Source: own study

should be noted that the inefficiency of crop rotations in the simulated scenarios is compensated by an increased volume of fertilisers' application. Compared with the results obtained by the model based on Equation (3), the lower limit of the purchase price of corn, at which it becomes effective to grow it as a monoculture, decreases. This is due to the higher level of nutrient consumption of potatoes and, consequently, higher costs for fertilisation.

It should be noted that the values of N, P, K in Tables 1 and 2, that are significantly higher than those recommended for usage by practitioners (see e.g., KRASNOVS'KYY [2017]), are explained by modelling the situation of the absence of organic fertiliser application without taking into account the impact of predecessors on the content of nutrients in the soil and a linear dependency between yield and the number of applied fertilisers according to the balance model (Eq. 4). The latter, together with the low biological assessment of the "potato–potato" pair in crop rotation, explains the significantly high fertiliser application rates modelled for year 3.

In addition, it should be noted that the coefficients of the input models used in the paper, that are available in the scientific and practical literature, are for the conditions of Ukraine, mostly outdated and require experimental studies or expert evaluation to update them. On the other hand, currently, freely available tools for assessing fertiliser rates (see, e.g., IAS "Ahrariyi razom" [undated]) generate values of the same order of magnitude as the proposed models: the total amount of active substance equals 641 kg·ha^{-1} for an anticipated corn yield of 14 Mg·ha^{-1} compared with 989 kg·ha^{-1}, according to Table 2. Similarly, for potato yield, it equals 60 Mg·ha^{-1}, the software on the above-mentioned website proposes a value of 679 kg·ha^{-1} compared with 904 kg·ha^{-1}, according to Table 2.

In the case of the model based on Equation (1), using the proposed algorithm we simulated crop rotations on three fields with areas equal to 1.5, 2.2, and 3.6 ha for the purchase price of corn equal to 0.17 EUR·kg^{-1}. The simulation was carried out for the case of crops' prices variance equal to 0.1 and fertilisers' prices variance equal to 0.2.

When riskiness increases, the system suggests replacing the "potato – potato – corn" crop rotation with ones less saturated by potato with an introduction of winter wheat. Such a recommendation is grounded on the fact that the risk of fertilisers' prices' increase makes the efficient growing of crops less dependent on fertilisation. Conducted in Ukraine, experimental studies on crop rotations [HOSPODARENKO *et al.* 2019] containing corn and wheat confirm the effectiveness of this approach. The recommendations generated by the proposed algorithm also include the use of crop rotations with a larger variance of potential profit on smaller fields, whereas on larger fields it is recommended to grow crops within less risky crop rotations.

When modelling crop rotations on one field according to the model based on Equation (2) that takes into account the dependency of yield on irrigation rate for water price equal to 0.032 EUR·m^{-3}, that is up-to-date for the year 2020, corn growing as a monoculture is effective when the purchase price is higher than 0.81 EUR·kg^{-1}. An increase in water price above 0.32 EUR·m^{-3} also made such practice inefficient. The economically efficient crop rotation for the purchase price equal to 0.17 EUR·kg^{-1} is given in Table 3. In the case given in Table 3, the predicted yield of corn is relatively low with a low rate of fertiliser application and seasonal irrigation rate. Thus, the model shows the lack of economic efficiency of growing corn compared to the potato at the current level of prices for water and fertilisers. In the case of potatoes, watering with a reduced irrigation rate is proposed because the cost of watering with higher rates, according to the model, is not compensated by additional income from increased yield.

In the case of the model based on Equation (2), using the proposed algorithm, we simulated crop rotations on three fields with areas equal to 1.5, 2.2, and 3.6 ha for the purchase price of

Table 3. Crop rotation obtained using the model based on Equation (2) for the price of corn equal to 0.17 EUR·kg^{-1} and the irrigation water price equal to 0.032 EUR·m^{-3}

Crop	Yield (Mg·ha^{-1})	Seasonal irrigation norm (m^3·ha^{-1})	N	P	K	Total expenses (EUR·ha^{-1})
			kg·ha^{-1}			
Year 1: potato	51	1054	225	46	350	369
Year 2: potato	51	1054	500	125	732	764
Year 3: corn	12	2390	363	172	454	591

Source: own study

corn equal to 0.17 EUR·kg^{-1}. The simulation was conducted for the case of fertilisers' price variance equal to 0.2, the basic variance of crops' price equal to 0.1, and the variance of irrigation water price equal to 0.002. Even at a high level of riskiness, the use of crop rotation given in Table 3 in all three fields was effective, according to the model. The obtained values of expenses on irrigation and fertiliser application are in good correspondence with the optimal expenses level of 493–704 EUR·ha^{-1} reported for the conditions of Ukraine by OSTAPENKO *et al.* [2020].

Summarising the obtained results, we can state that with an increase in the number of factors taken into account in the crop rotations model, it proposes growing corn as a monoculture in less restricted situations. The threshold price under which such practice becomes ineffective is lower from 1.13 EUR·kg^{-1}, in the case when expenses were not taken into account, down to 0.81 EUR·kg^{-1}, in the case when all factors were considered. Adequately reflecting modern practices, models propose to compensate for the biological inefficiency of monoculture with increased volumes of fertilisers and irrigation applications.

Confirming an initial hypothesis, consideration of uncertainties leads to different recommendations that consist of introducing crops that are less dependent on fertilisation and irrigation in the case when there is a great risk of an increase in the corresponding prices. A refined model, which considers growing crops on a set of fields, showed another possibility of risk diversification proposing lowering crop rotation riskiness with an increase in the field area.

CONCLUSIONS

In the paper, we propose the statement and the algorithm for solving the multicriterial problem of selecting crop rotations optimal by economic and ecological criteria under conditions of uncertainty. Costs of fertilisers and irrigation water were considered as expenses. Price parameters of economic models were considered in the form of random variables with normal distribution.

The negative impact of agricultural activity on the environment was assumed to be associated with the number of nitrogen fertilisers introduced into the soil. To perform such a multicriterial optimisation, three embedded problems must be solved. Due to high computational complexity, we propose to solve them by the metaheuristic method – the genetic algorithm.

Simulating optimal crop rotation selection, we analysed the efficiency of growing corn as a monoculture depending on the mean and variance of purchase prices and the price of irrigation water. The simulation showed a reduction in the economic effect of such practice with the decrease of the purchase price of corn below 0.81 EUR·kg^{-1} and an increase of irrigation water price above 0.32 EUR·m^{-3}.

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