Linear-dynamic model of the problem of optimization of placement and alternation of crops in cropping rotation

D T Muhamediyeva[1*], *M R* Rakhmonova[2], and *D M* Sotvoldiyev[3]

[1]"Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University, Tashkent, Uzbekistan
[2]Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, 108, Amir Temur Avenue, Tashkent, 100084, Uzbekistan
[3]Fiscal Institute of the Tax Committee under the Ministry of Economy and Finance of the Republic of Uzbekistan, Uzbekistan

Abstract. The problem of determining the best positioning and rotation of crops within fields of crop rotation has been approached through two different methods, static and dynamic. In the static model, specific schemes are chosen based on the predetermined number and size of rotation fields that can accommodate a particular crop. The model takes into consideration various factors such as crop yields within the same field, cotton production volume, labor costs, production expenses, and conditional net income. The optimization criterion in this model is to minimize production costs and maximize conditional net income, which is the difference between the costs of gross output per hectare and production expenses per hectare. The initial data is computed using long-term farm data, and information is prepared for each crop rotation scheme to enable a comprehensive evaluation of all crop rotation schemes and fields while taking into account major indicators of farm production.

1 Introduction

The enhancement of land fertility is contingent upon the implementation of comprehensive measures, which chiefly involve appropriate soil tillage, the introduction of scientifically grounded crop rotation systems, as well as the utilization of fertilizers, irrigation, and other agro-technical measures. The development and implementation of sound cotton crop rotation systems by each farm are important factors in improving the agricultural practices [1-3].

The pivotal aspect of crop rotation lies in the sequence of crop alternation as per the predetermined scheme. The absence of crop rotation across fields renders the system ineffective. The even rotation of crops necessitates the uniform size of crop rotation fields; otherwise, organizing crop rotation becomes arduous, ultimately resulting in the disruption

* Corresponding author: dilnoz134@rambler.ru

of the established crop rotation. Hence, considerable emphasis should be placed on maintaining uniform field sizes, which is interrelated to the number of crop rotations introduced and the subsequent alternation of crops [4-5].

The implementation and advancement of a specific cotton crop rotation scheme (such as one, two, etc.) in cotton farms substantially shapes the distribution of cultivated areas, the specialization of complementary industries, and the stabilization of agricultural production structure. This, in turn, lays the groundwork for enhancing the agricultural practices, augmenting the effectiveness of resource utilization, including land, labor, machinery, fertilizers, and other production inputs. Hence, it is essential to tailor optimal crop rotation systems to each farm, in accordance with their economic factors, to eradicate uniformity [6].

The initiation of crop rotations in any farm begins with the selection of a suitable type and rotation scheme from the recommended options, catering to the specific soil conditions. If one or two rotation schemes are prescribed for a given soil type, then no complications are anticipated. However, if there are multiple schemes and an uncertain number of on-farm subdivisions, the selection of an appropriate crop rotation scheme linked to the production, economic, and financial circumstances of the farm becomes challenging. In such cases, laborious computations are required to balance a plethora of factors. These computations can be effortlessly executed on a computer, provided there exists an adequate model of the process for selecting a crop rotation scheme. It is pertinent to take into account the size of agricultural land in individual soil zones, the dimensions of livestock industries, the combination of fodder crops in crop rotation, and several other conditions for specialization and production concentration within the farm while designing models for such problems [7].

Therefore, models designed for optimizing crop rotation systems in cotton farms should incorporate certain features and aspects of designing crop rotations in cotton growing [8].

2 Materials and methods

The linear-dynamic model for optimizing the placement and alternation of crops in a crop rotation can be expressed in the following form:

$$F_1(x) = \sum_{j=1}^{J} \sum_{\mu=1}^{\theta} c_{1j\mu} \cdot x_{1j\mu} \to \max,$$

$$F_2(x) = \sum_{j=1}^{J} \sum_{\mu=1}^{\theta} z_{1j\mu} \cdot x_{1j\mu} \to \min,$$

$$F_3(x) = \sum_{j=1}^{J} \sum_{\mu=1}^{\theta} \left(c_{1j\mu} - z_{1j\mu}\right) \cdot x_{1j\mu} \to \max,$$

Subject to the following restrictions and conditions:

$$\sum_{j=1}^{J} x_{rj\mu} = P_r \tag{1}$$

$$\sum_{j=1}^{J} x_{rj\mu} = x_{rj_0\mu+1} \tag{2}$$

$$-x_{rj_0\mu+1} + \sum_{j_1=1}^{J_1} x_{rj_1\mu+1} = 0 \quad (3)$$

$$\sum_{j=1}^{J}\sum_{i=1}^{J} \overline{\omega}_{ij\mu} x_{jm} \geq 0 \quad (4)$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R} u_{rj\mu} x_{rjm} \geq Q \quad (5)$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R}\sum_{\mu=1}^{\theta} u_{rj\mu} x_{rjm} \geq 0 \quad (6)$$

$$x_{rj\mu} \geq 0 \quad (7)$$

The following additional designations are adopted in the model: μ - rotation year number; θ - crop rotation period; $\overline{\omega}_{ij\mu}$ - norms for the cost of labor, mineral and organic fertilizers per 1 hectare of the j -th crop in the μ -th year of crop rotation; Q - the volume of production of raw cotton in the first year of rotation; $x_{rj\mu}$ -sowing size of the j -th crop on the r -th field of crop rotation in μ year of rotation.

The economic significance of the limitations and conditions in the model can be described as follows. Equation (1) specifies the size of each crop rotation field according to the individual crop rotation scheme..Equalities (2 and 3) ensure the transition from the μ year to the $\mu+1$ year of rotation while maintaining the size of crop rotation fields. Equation (4) calculates the total labor resources, mineral, and organic fertilizer requirements of crop rotation crops and the overall economy by years of rotation.

Inequality (5) is used to set the upper limit for the volume of raw cotton production that can be achieved during the years of rotation. On the other hand, relation (6) helps to estimate the potential volume of production of other products from crop rotation crops during the same period. Finally, conditions (7) ensure that all variables involved in the optimization problem must have non-negative values.

A block-structured genetic algorithm with artificial selection is employed to solve the problem formulated in equations (1)-(7).

The suggested approach is based on combining the customary evolutionary genetic approach with the concepts of adaptive optimization [8], primarily the sequential complex method, which aims to determine the maximum or minimum values of functions with multiple variables [8-10]. Simultaneously, at every moment in time, the current population corresponds to the complex of points in the exploration area. Alongside the classic genetic techniques of mutation, crossover, and selection, the algorithm introduces additional search complex operators, including selection, reflection, stretching, and compression. Contrary to the traditional complex method, the algorithm suggests reflecting not just one of the weakest points in the complex, but instead a set of the poorest individuals of the population [11-13].

In the typical scenario, the optimization process utilizing the conventional sequential complex-method operates as follows: the goal is to determine the minimum value of a given unction.

$$E(x)=\left(\sum_{j=1}^{J}\sum_{\mu=1}^{\theta} z_{1j\mu}\cdot x_{1j\mu}-\sum_{j=1}^{J}\sum_{\mu=1}^{\theta} c_{1j\mu}\cdot x_{1j\mu}+\left(\sum_{j=1}^{J} x_{rj\mu}-P_r\right)+\left(\sum_{j=1}^{J} x_{rj\mu}-x_{rj_0\mu+1}\right)\right)\rightarrow \min$$

Regrettably, there are hardly any beforehand suggestions made regarding the characteristic of this function, which is of a relatively broad type. The algorithm commences with creating the original intricate group of chromosomes, positioned quite randomly throughout the exploration area with -dimensions.

$$x_i(0)=\begin{pmatrix} x_1(0)\\ x_2(0)\\ \vdots\\ x_N(0)\end{pmatrix}=\begin{pmatrix} x_{11}(0) & x_{12}(0) & \dots & x_{1n}(0)\\ x_{21}(0) & x_{22}(0) & \dots & x_{2n}(0)\\ \vdots & & & \\ x_{N1}(0) & x_{N2}(0) & \dots & x_{Nn}(0)\end{pmatrix} \qquad i=\overline{1,N}\geq n+1$$

From the outset, selective maneuvers are executed, subsequently followed by hybridization and alteration. Consequently, a fresh group of chromosomes is produced.

Following this, the selection process is carried out. At this phase, the function's value is assessed in all chromosomes, and the mean health of the population is computed:

$$E_{сред}=\frac{1}{N}\sum_{i=1}^{N}E(x_i(k))$$

Afterwards, chromosomes with below-average health for the whole population are substituted with the "superior" chromosome:

If $E_{сред}<E(x_i(k))$ then $x_i(k+1)=x_i(k)$, which gives $\underline{\min}_{i=1,N}(E(x_i(k)))$.

Among the set $x_i(k)$ there is the “worst” one such that

$$E(x_H(k))=\min_i\{E(x_1(k)),\dots,E(x_H(k))\},$$

Then, the population's center of gravity is established, excluding the poorest point:

$$x_{cj}(k)=(x_{1j}(k)+x_{2j}(k)+\dots+x_{Nj}(k)-x_{Hj}(k))/(N-1) \qquad j=\overline{1,n}$$

Further, $x_H(k)$ is reflected through the center of gravity $x_c(k)$, forming a new top of the $x_R(k)$ complex, which is theoretically located closer to the extremum than $x_H(k)$ and $x_c(k)$, i.e.

$$E(x_R(R))<E(x_c(k))<E(x_H(k)).$$

The reflection operation formally has the following form:

$$\begin{aligned} x_R(k)&=x_c(k)+\eta_R(x_c(k)-x_H(k))=\\ &=\frac{1}{N-1}x_1(k)+\dots+\frac{1}{N-1}x_{N-1}(k)+\frac{\eta_R}{N-1}x_1(k)+\cdots\\ &+\frac{\eta_R}{N-1}x_{N-1}(k)-\eta_R x_H(k)=X(k)R,\end{aligned}$$

Where $\eta_R$is the reflection step parameter, often set equal to one, $X(k)=(x_H(k),x_1(k),\dots,x_{N-1}(k))$ is the (n×N)-vertex coordinate matrix complex, , $R=\left(-\eta_R,\frac{1+\eta_R}{N-1},\dots,\frac{1+\eta_R}{N-1}\right)^T-(N\times 1)$-vector.

If the reflection vertex $x_R(k)$ turns out to be the “best” among all other populations of chromosomes, i.e.

$$E(x_R(k))<E(x_i(k))<E(x_H(k)), \qquad i=1,2,\dots,N-1,$$

The complex is stretched in the direction from the center of gravity $x_C(k)$ to $x_R(k)$ according to the expression

$$x_E(k) = x_C(k) + \eta_E\left(x_R(k) - x_C(k)\right) = X(k)E,$$

Where η_E is the stretching step parameter, often set equal to two,

$$E = \left(-\eta_E, \eta_R, \frac{1-\eta_E(1-\eta_R)}{N-1}, \ldots, \frac{1-\eta_E(1-\eta_R)}{N-1}\right)^T.$$

If $x_R(k)$ turns out to be the worst among all $x_i(k)$, the complex shrinks according to the relation:

$$x_S(k) = x_C(k) + \eta_S\left(x_R(k) - x_C(k)\right) = X(k)S,$$

Where η_S is the compression step parameter, usually set equal to 0.5,

$$S = \left(-\eta_S, \eta_R, \frac{1-\eta_S(1-\eta_R)}{N-1}, \ldots, \frac{1-\eta(1-\eta)}{N-1}\right)^T.$$

The passage describes a modification of the complex method that integrates the Holland genetic procedure to create an algorithm that embodies the notion of artificial selection. In this modified approach, the complex method is used to construct a complex of N points-vertices, and at each iteration, the group loses one inferior vertex while acquiring one fresh point towards the extreme value of the optimized function.

The approach is similar to genetic algorithms in that multiple inferior individuals are eradicated from the population in every iteration due to selection. However, in this approach, the simultaneous formation of their "antipodes" with enhanced characteristics is also considered.

By integrating this modification with the Holland genetic procedure, an algorithm is created that embodies artificial selection. This approach can potentially lead to better optimization results by combining the strengths of both the complex method and genetic algorithms.

The performance of such an algorithm is composed of a series of the subsequent phases:

- Creation of an initial population formed by $P(0)$ chromosome individuals - the vertices of the complex.
- Crossoveroperationtoincreasethepopulationof $P_{CR}(0) > P(0)$.
- Mutationoperation $P_M(0) > P_{CR}(0)$.
- First selection (determination of the worst individuals) without population reduction $P_{SEL1}(0) = P_M(0)$.
- Operation of choice - we replace the values with the best one in the entire population.
- Operation of reflection with the removal of P of the worst $P_M(0) < P_{SEL1}(0)$ individuals.
- Sretching operation without increasing the population $P_E(0) = P_R(0)$.
- Compression operation without increasing the population $P_I(0) = P_E(0)$.
- The second selection with the removal of $P_W(0)$ of the worst individuals $P_{SEL2}(0) = P_I(0) - P_W(0) = P(1)$ and the formation of the $P(1)$ population of the next iteration of the algorithm.

3 Results and Discussion

An examination of the outcomes of solving the problem via a linear dynamic model on a computer enabled the formulation of a comprehensive strategy for the arrangement and rotation of crops in the fields over the entire rotation cycle. The arrangement of crops in the rotation was based on their predecessors while keeping the field size unchanged. Forage crops were allocated based on their compatibility with other commonly used crops in agricultural practices. Cotton's antecedent crops ensure optimal soil fertility, establishing a conducive environment for the proper growth and development of the plant. The proposed arrangement of crops in the rotation fields governs the sequence of their rotation by the years of the cycle.

The rotation sequence is determined in line with the crop rotation scheme and requirements. After a specific number of years of cotton cultivation, the fields are planted with alfalfa in conjunction with cereals such as wheat or barley, or with corn and root crops or other crops, as stipulated by the crop rotation scheme. The proportion and size of forage crops must undergo some alterations in the sown area structure. According to the computer calculations, the proportion of alfalfa crops in the first year and previous years exhibit a change. The proportion of alfalfa crops in the first year increases, with an average increase of 6.2% over the rotation cycle compared to 4.5%. This increase serves as a necessary precondition for the successful implementation of the introduced crop rotation scheme on the farm throughout the rotation cycle. The proportion of maize crops increases slightly by 9.4% on average over the rotation cycle due to the implementation of the cotton-alfalfa-corn rotation scheme.

The calculation indicates a reduction in the sowing of other crops in the rotation wedge by 1.8% compared to the farm's plan of 2.6%. This decline is due to a decrease in rice crops, as some of the vacant land will be utilized for growing vegetables, gourds, and cotton. An evaluation of the current state of crop rotations in the investigated area has revealed that the technical aspects of cotton crop rotations have been extensively researched, and specific recommendations have been developed for different soil conditions in the region. However, the organizational and economic justification of crop rotations, considering production and economic circumstances of individual farms, has received little attention. This includes the selection of crop rotation systems, evaluation of crop rotation field yields, and linking placement plans with crop rotations. Farms with a crop rotation development level of 80% or higher show relatively high economic efficiency in agricultural production. These farms exhibit higher cotton yields and produce more products per 100 hectares of arable land with minimal labor and production costs.

4 Conclusion

To address the limitations of the static models, dynamic models can be developed that take into account the potential yield of the fields and the impact of previous crops on the current crop. These models can be based on mathematical programming techniques, such as nonlinear programming, mixed integer programming, or stochastic programming, and can incorporate various constraints and objectives, such as crop rotation requirements, land use limitations, irrigation capacity, and profit maximization.

Dynamic models can also be integrated with decision support systems (DSS) that provide farmers with real-time information on weather conditions, soil moisture, and crop growth, and help them make informed decisions on crop management practices, such as fertilization, pest control, and harvesting. DSS can be implemented using artificial intelligence techniques, such as machine learning, deep learning, and neural networks, that can learn from historical data and predict future outcomes based on the current state of the farm.

Overall, the development of dynamic models and decision support systems can help farmers optimize their crop rotations, increase their yields, and reduce their production costs, while also promoting sustainable agriculture practices and minimizing the environmental impact of farming.

That sounds like an innovative approach to optimizing crop rotation and could lead to more efficient and sustainable agriculture practices. By using a genetic algorithm with artificial selection, the system can quickly and reliably generate optimal crop rotation schemes that take into account a variety of factors such as soil conditions, climate, and crop yields. The resulting software could be a valuable tool for farmers and other stakeholders involved in crop production, helping them make more informed decisions about the placement and alternation of crops in their fields. This, in turn, could lead to more efficient use of resources, higher crop yields, and improved environmental sustainability.

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