Improvement of the ecological sustainability of short-term rotation under the aridization conditions

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Abstract. Reducing the use of pesticides is one of the priorities of sustainable agriculture. Therefore, the use of crop rotation is an opportunity to increase the ecological sustainability of agroecosystems. In connection with global climate changes, it is necessary to study the issue of increasing the productivity of crop rotations in conditions with uneven precipitation during the growing season. The purpose of the study was to assess the efficiency of short-term rotation in terms of grain yield taking into account consideration the main agro-climatic factors, as well as to identify the possibility of using a pesticide-free technology for crops cultivation under the aridization conditions. The highest productivity of the studied crop rotations was in five-field and four-field crop rotations with the inclusion of legumes and slow sowing crops. The grain yield from one hectare of arable land was 1.70-1.81 tons with an average productivity of all the studied crop rotations of 1.54 tons. According to the results of long-term research, it has been established that in order to achieve the optimal efficiency of agroecosystems during climate aridization, it is necessary to sow corn and grain sorghum, which can form stable yields in years different in meteorological conditions.

1. Introduction

Volatile grain prices and the tendency towards sustainable development are forcing agricultural producers to seek alternative methods to increase income diversity and protect soil fertility. Reducing the application of pesticides is one of the priorities in tendency towards sustainable agriculture [1]. Due to intensive farming practices, growing environmental concerns have spurred the development of innovative farming systems such as organic and integrated farming as alternative ways to reduce pesticide application over current traditional systems. Organic agriculture is a production system that has the potential to address numerous economic and environmental problems associated with traditional agriculture [2]. Integrated agriculture includes physical and biological regulation strategies for pest control while reducing the number of pesticides [3]. It is an intermediate between high-cost traditional farming and organic farming, which prohibits the application of synthetic pesticides and fertilizers. Organic and integrated agriculture combine the sharing of management approaches to replace synthetic resources [4].

Intensive farming systems have a negative impact on the ecosystem. Therefore, the use of crop rotation is an opportunity to increase the ecological sustainability of agroecosystems [5]. Taking into account the current economic situation and the generated demand from agricultural producers, the study of crop rotations with a short-term rotation is of particular interest. A scientifically based
approach to this problem can significantly increase the efficiency of crop production, reduce the cost of using agricultural machinery, and, at the same time, improve the agroecological situation by changing the structure of the soil, improving its agrophysical properties. An ecologically and economically feasible concept of agriculture in any soil-climatic zone should be based on the cultivation of crops with better biological properties, taking into account their environmental impact on soil fertility and the state of agrocenoses [6,7]. Crop diversification provides agronomic benefits such as pest, disease and weed control [8].

Significant prospects for biologization are in replacing part of the nitrogen of mineral fertilizers with biological nitrogen. It is necessary to produce new plant varieties with a high nitrogen-fixing ability [9]. As evidenced by the research results of A.V. Dedov and M.A. Nesmeyanov, when switching to environmentally friendly technologies for crop cultivation, it is necessary to activate biological processes. The main role in this process belongs to legumes, as they increase crop yields. The transition to biologized farming systems ensures simulating natural phytocenoses, but with a higher productivity potential, and reducing degradation processes. Saturation of field crop rotations with leguminous crops should become a mandatory element of such systems [10]. According to long-term studies in Denmark, legumes in organic rotations can maintain nitrogen fixation without significantly affecting long-term fertilization regimes or fertility measures [11]. The impact of the introduction of leguminous crops into crop rotations was also assessed from an economic point of view. Studies have shown that rotations that include legumes have equal or higher gross margins than reference rotations without these crops [12].

R.G. Smith, K.L. Gross and G.P. Robertson examined the effect of changing the number of species in a crop rotation on grain yield that is a critical indicator of the ecosystem function of crops. Results indicate that agronomic research motivated by ecological theory can provide important information about the functioning of agroecosystems and enhance understanding of the interrelation of the diversity and function of ecosystems. Importantly, these results suggest that reducing chemical costs does not necessarily lead to lower yields and maintains crop diversity [13].

In this context, it is necessary to study the problem of increasing the productivity of crop rotations in conditions with uneven precipitation during the growing season. Scientists of the Federal Agricultural Research Center for South-East Region made a significant contribution to the development of agriculture in the arid chernozem steppe of the Lower Volga region. They carried out long-term studies to identify the possibility of increasing the sustainability of grain production by using grain crops with a time-shifted passage of interphase periods in crop rotations with different specific gravity of the fallow field and agricultural crops. It was revealed that in order to increase the stability of agricultural production, it is necessary to cultivate crops of various biogroups in arid conditions (winter, early spring and late crops) [14, 15].

A.V. Kislov, A.P. Glinushkin proved that introduction of five- and six-field crop rotations with complete fallow, which ensures the sowing of winter crops with a high competitive ability, the introduction of crops with a late sowing period and two pre-sowing treatments into the crop rotation makes it possible to exclude application of herbicides and thereby reduce the environmental impact on the harvest [16].

Most farms in Russia use traditional farming systems with a high technical and anthropogenic impact and irrational use of arable land. In this regard, it is necessary to develop new and adjust the previously proposed measures to ensure the stabilization of agricultural production with a steady reduction in the negative impact on the environment.

The purpose of the study was to assess the efficiency of short-term rotation in terms of grain yield taking into account consideration the main agro-climatic factors, as well as to identify the possibility of using a pesticide-free technology for crops cultivation in the Lower Volga region of the Russian Federation.

In our studies, the development of crop rotations was based on the cultivation of complementary groups of plants according to the principle of asynchronous passage through the ontogenesis stages. In addition to winter and early spring cereals, late crops were cultivated in crop rotations. The inclusion
of drought-resistant late crops can compensate for the yield losses of other crops and ensures the stabilization of the yield [17].

2. Materials and methods

The research was carried out in 2008-2019 on the experimental field of the Russian Research Institute for Sorghum and Maize “Rossorgo”, located in the southern Right-bank microzone of the Saratov region of the Russian Federation. The zone of the arid chernozem steppe of the Volga region is is arid and sharp continental. The annual amount of precipitation is 420-480 mm. During the growing season, there is 200-250 mm of precipitation. The sum of active temperatures above 10°C is 2400-2800 °C. The average annual air temperature in the chernozem steppe is 4.1-5.2 °C.

The weather conditions during the research were different and covered the entire set of climatic features of the region: out of twelve years, 2008, 2013 and 2017 were yielding and favorable in terms of moisture (hydrothermal index is 1.0-1.2). On average, over these years, 282 mm of precipitation fell in April–August, and the sum of active temperatures was 2679 °C. 2009, 2014, 2015, 2016, 2018 and 2019 years were averages (hydrothermal index is 0.5-0.8). Atmospheric precipitation in April–August is 174 mm, the sum of active temperatures is 2884 °C. 2010-2012 years were dry and hot, (hydrothermal index is 0.3-0.4). The amount of precipitation in April–August was 107 mm, the average amount of active temperatures was 3160 °C.

The soil is southern medium-thick low-humus heavy loamy chernozem. The arable layer (at the time of the test) was characterized by the following indicators: humus content (according to Tyurin) was 4.85%, hydrolyzable nitrogen (according to Tyurin-Kononova) - 0.05%, mobile phosphorus (according to Machigin) - 4.53 mg per 100 g of soil, exchangeable potassium (according to Machigin) - 38 mg per 100 g of soil, pH of the salt extract - 6.6.

Agrotechnics are generally accepted for the area, without the application of pesticides. In autumn, one-time stubble cultivation and deep plowing by 25-27 cm for all crops were carried out. In winter, double snow retention was carried out. In spring, dust mulching, presowing cultivation for early crops and two cultivations for late crops were carried out. Sowing of winter and early spring crops was carried out at optimal times by a continuous row method using a SZ-3.6 seeder; sowing of arable crop was carried out by wide-row method with row spacing of 70 cm using a SO-4.2 seeder. In the summer, inter-row cultivation was carried out on arable crops. The black steam treatment consisted of 5 cultivations. The area of the accounting plot is 100 m², the placement is systematic, the repetition is threefold; the location is in two tiers.

Efficiency evaluated according to the yield of grain from one hectare of arable land of experimental crop rotations:

- three-field crop rotations - black fallow, winter wheat, spring wheat; black fallow, winter wheat, spring barley; black fallow, winter wheat, corn; black fallow, winter wheat, grain sorghum;
- four-field crop rotations - black fallow, winter wheat, soybeans, spring wheat; black fallow, winter wheat, soybeans, spring barley; black fallow, winter wheat, soybeans, corn; black fallow, winter wheat, soybeans, grain sorghum;
- five-field crop rotations - black fallow, winter wheat, spring wheat, chickpeas, grain sorghum; black fallow, winter wheat, spring barley, chickpeas, corn; black fallow, winter wheat, corn, chickpeas, spring barley; black fallow, winter wheat, grain sorghum, chickpeas, spring wheat.

The yield was estimated by the method of direct combining, by swathing on each plot separately. The main research results were subjected to statistical processing by the method of two-way ANOVA according to B.A. Dospekhov (2012) using the AGROS version 2.09.
3. Results and discussion

The main indicator for assessing the efficiency of crop rotations is the yield of products from the crop rotation area. The productivity of agroecocenoses was assessed both for the entire period of research and in years different in terms of agrometeorological conditions.

The formation of a biological yield in crop rotations largely depends on the conditions of the growing season and crop rotation; in the course of variance analysis, a different effect on the productivity of crop rotations of the above factors was noted (Figure 1–3). In three-field crop rotations, the share of the influence of the factor “weather conditions of the growing season” was 65.38%. The influence of crop rotation was also significant (the share of the factor's influence is 16.04%). In four-field crop rotations, variance analysis showed the reliability of the influence of the factors “weather conditions of the growing season” and “crop rotation” (77.87 and 4.80%, respectively). In five-field crop rotations, the share of the influence of the factor “weather conditions of the growing season” was 79.88%, while the share of the factor “crop rotation” was 0.25%.

![Figure 1](image1.png)
![Figure 2](image2.png)
![Figure 3](image3.png)

Figure 1. The share of the influence of factors “crop rotation” and “weather conditions of the growing season” on the productivity of three-field crop rotations

Figure 2. The share of the influence of factors “crop rotation” and “weather conditions of the growing season” on the productivity of four-field crop rotations

Figure 3. The share of the influence of factors “crop rotation” and “weather conditions of the growing season” on the productivity of five-field crop rotations.
The highest productivity among all the schemes of the studied crop rotations was in five- and four-field ones with the inclusion of leguminous and late crops. The grain yield from one hectare of arable land amounted to 1.70-1.81 tons with an average productivity of all the studied crop rotations of 1.54 tons.

In three-field crop rotations, the maximum grain yield was in the variants with late crops, such as grain sorghum and corn (Table 1). On average, productivity was higher by 0.37-0.76 tons in comparison with grain-fallow crop rotations. The same tendency is observed when assessing the productivity of crop rotations in years with different moisture levels.

In dry years, the differences in productivity with different crop rotation are more pronounced than in medium and wet years. Thus, the yield of grain from one hectare of arable land in grain-fallow crop rotations was 0.51-0.52 tons, and in grain-fallow crop rotations it was 0.80-0.92 tons. In medium years, in the variants with early spring crops the productivity was 1.26-1.29 t/ha.

In crop rotations with grain sorghum and corn, the average productivity was 1.62 and 1.73 t/ha, respectively. In dry and medium years, the difference in the productivity of crop rotations with fallow, winter wheat, spring wheat and fallow, winter wheat, spring barley is not significant, within the experimental error.

In wet years, the efficiency of crop rotations was higher. In crop rotations with spring wheat and barley, the grain yield per one hectare of arable land varied within 1.46-1.53 tons, in crop rotations with grain sorghum and corn - 1.96-2.22 tons, respectively. With the introduction of corn sown areas into the structure, the difference with other variants of the experiment is significant. In the crop rotation with grain sorghum, the excess of productivity is also significant in comparison with grain-fallow crop rotations.

Table 1. Grain yield per one hectare of arable land in three-field crop rotations depending on crop rotation in years of different moisture content (2008-2019), tons.

| Crop rotation (Factor A)                      | Weather conditions of the growing season (Factor B) | Average over factor A |
|----------------------------------------------|-----------------------------------------------------|-----------------------|
|                                              | hydrothermal index < 0.6                            | 0.52                  |
| Fallow, winter wheat, spring wheat           |                                                     | 1.29                  |
|                                              | 0.6 ≤ hydrothermal index ≤ 1.0                      | 1.46                  |
|                                              | hydrothermal index ≥ 1.0                            | 1.09                  |
| Fallow, winter wheat, spring barley          |                                                     | 0.51                  |
|                                              |                                                     | 1.26                  |
|                                              |                                                     | 1.53                  |
| Fallow, winter wheat, spring barley          |                                                     | 1.10                  |
| Fallow, winter wheat, corn                   |                                                     | 0.92                  |
|                                              |                                                     | 1.73                  |
|                                              |                                                     | 2.22                  |
| Fallow, winter wheat, grain sorghum          |                                                     | 1.62                  |
|                                              |                                                     | 1.96                  |
|                                              |                                                     | 1.46                  |
| Average over factor B                        |                                                     | 0.69                  |
|                                              |                                                     | 1.48                  |
|                                              |                                                     | 1.79                  |
|                                              |                                                     | -                     |
| Experimental error, %                        |                                                     | 13.03                 |
| $F_{0.05}$ (A)                               |                                                     | 7.184*                |
| $F_{0.05}$ (B)                               |                                                     | 43.804*               |
| $F_{0.05}$ (AB)                              |                                                     | 0.257                 |
| HCP$_{0.05}$ (A)                             |                                                     | 0.290                 |
| HCP$_{0.05}$ (B)                             |                                                     | 0.251                 |
| HCP$_{0.05}$ (AB)                            |                                                     | ns                    |

In four-field crop rotations, the grain yield from one hectare of arable land was higher than in three-field crop rotations, which is due to the inclusion of soybeans and a decrease in the proportion of black fallow to 25% (Table 2). The average productivity of agrogenoses was 1.38-1.76 t/ha. When examining the results of studies in years different in moisture, in grain-fallow crop rotations, an excess
of indicators was also revealed in comparison with grain-fallow crop rotations, differences in grain yield are significant in all variants of crop rotation.

Table 2. Grain yield per one hectare of arable land in four-field crop rotations depending on crop rotation in years of different moisture content (2008-2019), tons

| Crop rotation (Factor A)                      | Weather conditions of the growing season (hydrothermal index) (Factor B) | Average over factor A |
|----------------------------------------------|-------------------------------------------------------------------------|-----------------------|
|                                              | hydrothermal index < 0.6 | 0.6 ≤ hydrothermal index ≤ 1.0 | hydrothermal index ≥ 1.0 |
| Fallow, winter wheat, spring wheat           | 0.59                      | 1.47                          | 2.14                      | 1.40                      |
| Fallow, winter wheat, spring barley          | 0.58                      | 1.43                          | 2.12                      | 1.38                      |
| Fallow, winter wheat, corn                   | 0.88                      | 1.79                          | 2.61                      | 1.76                      |
| Fallow, winter wheat, grain sorghum          | 0.83                      | 1.69                          | 2.43                      | 1.65                      |
| Average over factor B                        | 0.72                      | 1.60                          | 2.32                      | -                        |
| Experimental error, %                        | 10.15                     |                                |                          |
| F<sub>0.05</sub> (A)                         | 4.286*                    |                                |                          |
| F<sub>0.05</sub> (B)                         | 104.383*                  |                                |                          |
| F<sub>0.05</sub> (AB)                        | 0.086                     |                                |                          |
| HCP<sub>0.05</sub> (A)                       | 0.265                     |                                |                          |
| HCP<sub>0.05</sub> (D)                       | 0.230                     |                                |                          |
| HCP<sub>0.05</sub>(AB)                       | ns                        |                                |                          |

In dry years (hydrothermal index < 0.6), the grain yield in crop rotations with early spring crops varied within 0.58-0.59 t/ha, in crop rotations with late crops - 0.83-0.88 t/ha. In the years with average moisture (0.6 ≤ hydrothermal index ≤ 1.0), the difference in the productivity of experimental crop rotations was less significant. In variants with spring wheat and barley, productivity was 1.43-1.47 t/ha, with the inclusion of grain sorghum and corn - 1.69-1.79 t/ha, respectively.

In wet years (hydrothermal index ≥ 1.0), the maximum indicators were obtained for all variants of the experiment. In grain-fallow crop rotations, the grain yield from one hectare of arable land was 2.12 tons in crop rotations with barley, 2.14 tons in crop rotations with spring wheat. Late crops significantly increase the productivity of agrocenoses. The grain yield was 2.43 t/ha in crop rotations with grain sorghum and 2.61 t/ha in crop rotations with corn.

In five-field crop rotations, a high level of productivity indicators was in all variants, which is associated with the presence of corn and grain sorghum in all crop rotations, as well as with the inclusion of chickpeas and a decrease in the proportion of black fallow to 20%. At the same time, the efficiency of schemes with the inclusion of corn is higher. On average, the grain yield from one hectare of arable land in such crop rotations was 1.79-1.81 tons. The productivity of crop rotations with grain sorghum in the second and fifth fields of crop rotations is 1.70-1.73 t/ha.

In years of different moisture content, the productivity of five-field crop rotations was significantly different. In dry years, the differences between the variants of the experiment are less pronounced, the grain yield was 0.80-0.85 t/ha. In wet years, the difference between crop rotations is more pronounced. The productivity of crop rotations with grain sorghum was 2.51-2.57 t/ha, with the inclusion of corn it was 2.64-2.68 t/ha (Table 3).
Table 3. Grain yield per one hectare of arable land in four-field crop rotations depending on crop rotation in years of different moisture content (2008-2019), tons.

| Crop rotation (Factor A) | Weather conditions of the growing season (hydrothermal index) (Factor B) | Average over factor A |
|--------------------------|-------------------------------------------------|---------------------|
|                          | hydrothermal index < 0.6 | 0.6 ≤ hydrothermal index ≤ 1.0 | hydrothermal index ≥ 1.0 |
| Fallow, winter wheat, spring wheat | 0.80 | 1.81 | 2.51 | 1.70 |
| Fallow, winter wheat, spring barley | 0.85 | 1.88 | 2.64 | 1.79 |
| Fallow, winter wheat, corn | 0.85 | 1.89 | 2.68 | 1.81 |
| Fallow, winter wheat, grain sorghum | 0.81 | 1.81 | 2.57 | 1.73 |
| Average over factor B | 0.83 | 1.85 | 2.60 | - |

Experimental error, %

- F₀.05 (A) 0.169
- F₀.05 (B) 78.970*
- F₀.05 (AB) 0.169
- HCP₀.05 (A) ns
- HCP₀.05 (B) 0.293
- HCP₀.05 (AB) ns

4. Conclusion

In the course of the research, it was found out that in order to achieve the optimal efficiency of agrocenoses under conditions of climate aridization, it is necessary to include late crops, such as corn and grain sorghum in the structure of sown areas, as they can form stable yields in years different in meteorological conditions. It is also advisable to include leguminous crops, which increase the efficiency of crop rotations and contribute to the preservation of soil fertility.

In arid conditions, it is recommended to use short-term crop rotations with fallow, winter wheat, soybeans, grain sorghum: fallow, winter wheat, soybeans, corn: black fallow, winter wheat, spring wheat, chickpeas, grain sorghum; black fallow, winter wheat, spring barley, chickpeas, corn; black fallow, winter wheat, corn, chickpeas, spring barley; black fallow, winter wheat, grain sorghum, chickpeas, spring wheat. Such crop rotations provide 1.65-1.81 tons of grain from one hectare of arable land. Long-term research confirms that when a wide range of crops is included in the structure of sown areas, it is possible to exclude the application of pesticides.

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