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Priorities for Sustainable Development of Regional Agri-Food Systems in the Context of Achieving Food Security

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Abstract

The study presents methodological approaches to developing regional agri-food strategies integrating economic, social, and environmental indicators, aiming to improve socio-economic and environmental efficiency in the context of food security. To assess regional sustainable development, a hierarchical cluster analysis using Ward's method was applied to compare Russian regions based on indicators of agricultural specialization, economic efficiency, food security, social conditions, and environmental impact. The analysis identified seven distinct regional clusters with significant socio-economic and environmental differences. A critical finding is that all clusters exhibit persistent problems with waste disposal and neutralization, alongside an acute shortage of investment for technological modernization and additional processing capacity. Key priorities for improving efficiency in achieving food security are identified, and differentiated sustainable development strategies for the selected groups are proposed, including recommendations for adapting governance mechanisms and state support. The need for fundamentally new forms of financing innovative businesses is substantiated. This study provides a differentiated framework for developing regulatory tools for regional agri-food systems based on cluster analysis results. The findings have practical value for planning socio-economic and environmental development programs and for formulating state innovation policy in agricultural support.

Keywords: agricultural specialization; monitoring; cluster analysis; regional agricultural systems; food security; management strategies; social environment; government support; economic efficiency; ecological balance

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1. Introduction

The diversity of natural, climatic, social, and economic conditions under which regional agri-food systems operate necessitates the development of differentiated territorial development strategies.

The high degree of differentiation among Russian regions in terms of natural and climatic conditions, socioeconomic development, and the environmental sustainability of agri-food systems necessitates the development of sustainable development strategies for various groups of regions to achieve food security and integrated rural development.

The aim of this study is to assess the sustainable development of regional agri-food systems using economic, social, environmental, and food security indicators and to justify effective regional mechanisms for improving socioeconomic and environmental performance in support of food security.

This paper addresses the following logically interconnected research questions:

RQ 1. What differences exist among Russian regions in terms of the economic, food, social, and environmental sustainability of their agri-food systems?

RQ 2. Can cluster analysis be used to identify statistically homogeneous groups of regions requiring different sustainable development strategies?

RQ 3. Which government policy instruments are most effective for different types of regional agri-food systems?

The methodological framework of this study is based on the following theoretical approaches: the Sustainable Development Concept, Resilience Theory, Systems Theory, Socio-Ecological Systems Theory, and the Triple Bottom Line framework. In particular, the concept of sustainable agricultural development provides a practical framework for balancing three key objectives: ensuring food security, conserving natural resources, and maintaining a decent standard of living for rural populations and agricultural producers. Resilience Theory views agricultural systems not as static entities but as complex adaptive systems that are continually exposed to shocks, such as climate extremes, market fluctuations, pandemics, and natural disasters, while maintaining the capacity to adapt and recover. Socio-Ecological Systems Theory emphasizes the dynamic interactions and feedback mechanisms between social and ecological subsystems. The Triple Bottom Line framework evaluates the performance of systems across three dimensions: economic, social, and environmental.

Region classification utilizes a modeling and clustering methodology based on hierarchical cluster analysis using Ward's method with the squared Euclidean distance as a measure of proximity. Sustainable regional development is assessed by comparing Russian regions based on indicators of agricultural specialization, economic efficiency, food security, social environment, and environmental impact.

The scientific significance of the proposed approach lies in providing a comprehensive assessment of the resilience of regional agri-food systems by explicitly incorporating the food security subsystem into the analytical framework.

The scientific novelty lies in the differentiated approach to the development of tools and strategies for government regulation of regional agri-food systems and groups of regions based on the results of the conducted cluster analysis. The results of the study can be taken into account when adjusting regional sustainable development policies and demonstrate the potential for using the developed assessment and forecasting tools for diagnosing and monitoring the state of regional agri-food systems.

The academic contribution of this study consists of the use of cluster modeling methodology and tools to analyze the relationship between indicators of agricultural specialization, economic efficiency, food security, the state of the social environment, and environmental effects, the development of tools for diagnosing the problem, and the improvement of mechanisms for managing the sustainable development of regional agri-food systems.

2. Literature Review

The issues of sustainable development are widely represented in the scientific publications of modern researchers. Content analysis of scientific publications was conducted in the following main areas of scientific research: sustainable development of agri-food systems; regional development strategies; and cluster analysis methods.

The methodology for developing regional agribusiness development strategies is widely discussed in modern literature; it is based on a rational combination of scientific approaches such as foresight, scenario, cluster, and project-based approaches [1,2]. For example, in European Union countries, agricultural development models are based on the concept of multifunctional agriculture, which includes achieving food security, regulating ecological balance, and supporting rural incomes [3–5].

Significant attention is paid to methodological issues of developing effective strategies for agricultural development [6–8]. It is appropriate to identify the impact of the strategies of the related agro-industrial complex sectors on agriculture [9]. The undeniable importance of using regional innovation strategies to enhance the competitiveness of the agricultural sector is emphasized in reference [10].

Agricultural development strategies in Southeast Asian countries are based on long-term forecasting, the development of efficient supply chains [11], the widespread use of digital technologies [12] and innovations [13]. Chinese scientists propose considering spatial-temporal characteristics and probable development scenarios using a specific set of regional indicators when developing agricultural development strategies [14]. In some Chinese provinces, greening strategies for the agricultural sector, supported by budgetary payments, are actively being implemented [15]. Researchers in this field conclude that economic factors play a restraining role in the development of a “green” economy. To study the impact of budget subsidies on the development of “green” agriculture, it is proposed to consider the level of achieved productivity in individual regions [16].

Modern research on sustainable development of agricultural systems in Russia highlights competitive advantages, food security, and financial sustainability as the most important priorities when choosing regional strategies [17–21]. Developing these provisions, reference [22] demonstrates that the problem of achieving food security leads to an agricultural market equilibrium in a state of Pareto inefficiency, which determines the need for government intervention and support for the production process. Recognizing the undeniable role of agricultural entrepreneurship, reference [23] notes the need for further improvement of the institutional environment to enhance the competitiveness of small businesses.

The strategic development of the regional agro-industrial complex should be focused on the efficient use of production potential, taking into account global economic, technological, and social risks. Therefore, the authors of the cited work substantiate recommendations for improving regional innovation and investment activities with the aim of increasing the efficiency of resource potential use and increasing exports.

Differentiated strategies for state regulation were proposed for cluster groups of regions, taking into account certain criteria for agricultural sustainability [24]. The lack of coordination between federal and regional policies often results in competition for investment with other regions [25].

Reference [26] presents a scientifically substantiated approach to developing an effective decision-support tool for assessing the effectiveness of new production strategies aimed at the sustainable development of agricultural enterprises while taking climate-related challenges into account. The need to improve structural policies for rural development is also emphasized in reference [27]. This study revealed significant regional disparities in the availability of production infrastructure and highlighted the need for additional financial resources.

Certain methodological approaches to developing regional strategies include recommendations for using cluster methods and intellectual specialization strategies as the basis for developing innovative entrepreneurship centers [28,29]. Strategic decision-making on agricultural development largely depends on the established relationships between regions with different specializations [30].

Innovation investment strategy as a priority for agricultural sector development is considered in most African countries, highlighting as the optimal scenario a 10% increase in public funding for agricultural research in the near future, which would ensure a 6% increase in production by 2030 [31]. A necessary condition for implementing such a scenario is improving mechanisms for stimulating the dissemination of knowledge and innovation.

In the global scientific discourse, a prerequisite is the use of indicators of regional and rural socioeconomic development, as well as analysis and evaluation of leading regions with high performance indicators, which allows for the identification of necessary priorities [32,33]. The analysis of the recent literature reveals general trends and identifies key challenges in the development of agri-food systems. Most existing studies focus on assessing individual dimensions of sustainability, whereas comprehensive assessments integrating economic, social, environmental, and food security dimensions at the regional level in Russia remain limited.

This study contributes to the ongoing scholarly discussion on the priorities for the sustainable development of regional agri-food systems in the context of ensuring food security.

3. Materials and Methods

Using Rosstat data on socioeconomic development and environmental conditions, a database covering the period 2019–2023 was compiled [34]. This database was used to analyze the functioning of agri-food systems across the regions of the Russian Federation and to classify them by identifying corresponding sustainable development models. The study also draws on findings from both Russian and international research.

The study utilized content analysis of scientific publications on regional agri-food system strategies and a systemic analysis of socio-economic and environmental indicators for typical regions within the selected groups. This approach allowed for the substantiation of corresponding sustainable development strategies for the selected groups of regions and the development of recommendations for further improvement of governance mechanisms and government support.

The stated objective of the study was achieved through the development of appropriate predictive and analytical tools for statistical analysis. The next indicators characterizing agricultural specialization, economic efficiency of agricultural production, food security, the state of the social environment, and environmental impacts were substantiated (Table 1).

The sustainability indicators for agri-food systems were selected in two stages. The first stage assessed whether the selected indicators were consistent with the conceptual framework underlying the respective dimensions of agri-food system sustainability. The relationship between each indicator and the concept of sustainable development was established, and its inclusion in the relevant sustainability dimension was evaluated in terms of its theoretical and practical significance. In addition, each indicator was assessed in terms of its responsiveness to government policy and comparability with internationally available statistical data.

The second stage involved a statistical screening procedure based on the following criteria: data availability for all 79 regions of the Russian Federation, absence of duplication, direction of impact on sustainability, spatial comparability, and the coefficient of variation. Each indicator was classified as either a positive indicator, for which higher values represent better sustainability performance, or a negative indicator, for which higher values represent poorer sustainability performance. Positive indicators were normalized as follows: (x-min)/(max-min); whereas negative indicators were normalized using: (max-x)/(max-min).

Table 1. List of indicators used in the statistical analysis.

X_1	The share of profitable agricultural enterprises, %
X_2	Investment in fixed capital in agriculture per hectare of agricultural land, rubles
X_3	Number of people employed in agriculture, thousands
X_4	Labor productivity in agriculture, thousands of rubles per person
X_5	Agricultural output per capita, thousands of rubles
X_6	Share of agricultural output in gross regional product, %
X_7	Proportion of the population with incomes below the subsistence level, %
X_8	Gini coefficient, basis points
X_9	Change in the rural population in 2023 compared to 2015, %
X_{10}	Share of small agricultural enterprises' turnover, %
X_{11}	Share of output produced by peasant (farm) households, %
X_{12}	Subsidies for integrated rural development per rural resident, rubles
X_{13}	Amount of state support funds for agricultural development programs per hectare of agricultural land, rubles
X_{14}	Self-sufficiency rate for meat and meat products. %
X_{15}	Milk and dairy product self-sufficiency rate, %
X_{16}	Potato self-sufficiency rate, %
X_{17}	Vegetable and melon self-sufficiency rate, %
X_{18}	Egg self-sufficiency rate, %
X_{19}	Food affordability, %
X_{20}	Share of captured and neutralized pollutants from stationary sources as a % of total waste
X_{21}	Waste disposal and neutralization in total waste, %
X_{22}	Index of physical volume of environmental protection expenditures, 2023/2022, %
X_{23}	Investments in fixed capital for environmental protection and rational use of natural resources per 10,000 rubles of gross regional product, rubles

Before the cluster analysis was performed, all indicators were normalized to eliminate the effects of differences in their measurement units on the classification results. A robustness analysis was subsequently conducted to assess the stability and validity of the resulting cluster solution.

The selection of indicators is based on contemporary international research in the field of sustainable development assessment and is explained by the availability of comparable official statistical data. The selected system of 23 indicators was developed conceptually rather than statistically. Each indicator reflects an independent aspect of the sustainability of the regional agri-food system and was not considered interchangeable with other indicators. Therefore, maintaining a full set of variables ensures a comprehensive assessment. Thus, indicators 1–6 characterize agricultural specialization and the economic efficiency of agricultural production, indicators 7–13 characterize the state of the social environment, indicators 14–19 characterize food security, and indicators 20–23 characterize environmental effects.

In improving the tools for sustainable development of agricultural systems, it is possible to draw on the achievements of modern research. For example, the analysis of environmental sustainability relies on indicators comparable with those available in

Russian official statistics, including greenhouse gas emissions from agricultural activities, the share of energy generated from renewable sources, resource-use intensity (fertilizer, pesticide, and water consumption per unit of output), indicators of agricultural land and water resource degradation, nutrient balances, and surface water quality [33].

The study is based on official international statistical data and reports published by the OECD [35], Eurostat [36], and the FAO [37]. In particular, the FAO uses sustainable development indices to provide a comprehensive assessment by integrating environmental, social, and economic dimensions. The OECD Better Life Index (BLI) [38] incorporates indicators of environmental quality, social connections, education, and health. European Union countries also use agri-environmental indicators to monitor and evaluate the implementation of the Common Agricultural Policy, including measures of soil and water quality and greenhouse gas emissions. In China, researchers have developed several national indicator systems that group sustainability indicators into such dimensions as resource conservation, environmental performance, and industrial development. For example, Reference [39] proposed the Environmental Human Index, which combines the Human Development Index and the Environmental Performance Index.

Using multivariate analysis methods, we can identify statistically valid territorial clusters with significant differences in indicators of agricultural specialization, economic efficiency, food security, the state of the social environment, and environmental impacts. Based on this, sustainable development strategies for the agrifood complex can be identified for the regions of each cluster, and recommendations for improving socioeconomic and environmental efficiency in achieving food security can be substantiated.

To eliminate the effects of differences in measurement scales, all variables were standardized prior to cluster analysis. For all indicators, a standardization algorithm was used using the formula:

$$ui = (xi - x\ avg)/si, \tag{1}$$

where xi is the indicator used in clustering regions; x avg is the mean value of the i-th variable; and si is the standard deviation of the i-th variable.

The application of cluster analysis in this study resulted in the classification of Russian regions into several groups with a high degree of homogeneity across the above set of indicators (Table 2).

Table 2. Characteristics of clusters according to sustainability indicators of Russian agri-food systems.

Average Values of Indicators by Cluster Regions	Cluster 1 (13 Regions)	Cluster 2 (11 Regions)	Cluster 3 (26 Regions)	Cluster 4 (25 Regions)	Cluster 5 (Murmansk Region)	Cluster 6 (2 Regions)	Cluster 7 (Chukotka Autonomous Okrug)
Economic sustainability							
Proportion of profitable agricultural enterprises, %	77.0	76.2	76.5	67.9	67.4	54.8	81.0
Volume of investment in agricultural fixed capital per hectare of agricultural land, rubles	5587.6	5245.0	3736.1	6946.0	590,110.2	16,873.4	10.1
Number of people employed in agriculture, thousands	53.3	37.4	72.8	53.8	8.6	8.2	1.3
Labor productivity in agriculture, thousands of rubles per person	1206.3	1263.3	1111.3	2118.6	3667.5	2572.7	4407.6
Agricultural output per capita, thousands of rubles	141.3	62.9	77.8	35.2	4.1	31.0	40.5
Share of agricultural output in the gross regional product, %	15.3	6.7	12.0	3.9	7.1	3.1	2.1

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Table 2. *Cont.*

Average Values of Indicators by Cluster Regions	Cluster 1 (13 Regions)	Cluster 2 (11 Regions)	Cluster 3 (26 Regions)	Cluster 4 (25 Regions)	Cluster 5 (Murmansk Region)	Cluster 6 (2 Regions)	Cluster 7 (Chukotka Autonomous Okrug)
Food sustainability							
Self-sufficiency rate for meat and meat products. %	402.3	120	83.4	60.3	1.3	27.1	22.7
Milk and dairy product self-sufficiency rate, %	114.4	154.0	99.5	68.3	12.2	46.8	0.0
Potato self-sufficiency rate, %	155.0	99.7	85.6	86.2	13.7	79.2	5.3
Vegetable and melon self-sufficiency rate, %	101.8	64.7	105.7	48.8	0.9	48.2	17.6
Egg self-sufficiency rate, %	80.3	261.2	74.2	87.9	0.1	67.2	81.0
Economic accessibility of food, %	37.3	37.1	38.9	33.6	29.6	29.2	39.6
Social sustainability							
Proportion of the population with income below the subsistence level, %	9.4	9.8	13.8	10.2	6.7	11.2	5.2
Gini coefficient, basis points	0.373	0.364	0.376	0.427	0.349	0.411	0.353
Change in rural population in 2023 compared to 2015, %	92.9	91.0	97.3	94.6	89.0	87.0	92.1
Share of small agricultural enterprises' turnover, %	5.3	4.2	6.6	2.2	7.8	2.5	2.5
Proportion of output produced in peasant (farm) households, %	10.3	5.8	23.4	12.4	4.2	31.5	3.7
Subsidies for integrated rural development per rural resident, rubles	1185.1	1056.7	1064.5	1136.9	2651.2	52,942.9	282.0
Amount of state support funds for agricultural development programs per hectare of agricultural land, rubles	1268.2	1555.3	937.2	1633.8	34,237.1	653.6	162,096.7
Environmental sustainability							
Share of captured and neutralized pollutants from stationary sources as a percentage of total waste	57.5	49.7	43.6	62.8	92.7	57.6	44.4
Waste disposal and neutralization as a percentage of total waste, %	68.1	77.5	46.3	60.7	22.3	41.3	43.1
Index of physical volume of environmental protection expenditures, 2023/2022, %	100.5	107.2	107.4	110.2	104.4	302.5	84.5
Investments in fixed capital for environmental protection and rational use of natural resources per 10,000 rubles of gross regional product, rubles	197.6	352.9	106.6	1259.2	450.0	1093.9	1166.7

Compiled based on official statistics from Rosstat.

The use of the Ward hierarchical method with the squared Euclidean distance as a measure of proximity confirms the achieved high homogeneity of the clusters. Data visualization is represented by a dendrogram reflecting the step-by-step sequential combination of clusters based on the selected distance. The specified number of clusters was determined based on expert assessment.

The statistical database for this study includes data for 79 regions (subjects of the Russian Federation) for which complete information on all the listed indicators was available for the research period. The number of analyzed objects (79 regions) significantly exceeds the number of features used, which ensures sufficient stability of the clustering procedure. Calculations were performed using the SPSS statistical data processing and analysis package (IBM SPSS Statistics 27.0).

4. Results and Discussion

The convenience of hierarchical methods lies in the ability to represent the agglomerative process of cluster development as a tree (dendrogram). This process is easily visible and descriptive when the number of objects being classified is small (up to 150–200), so it is often used when the objects are regions [40].

The use of Ward's hierarchical method with the squared Euclidean distance as a proximity measure in this paper is justified by the fact that its algorithm leads to a sufficiently high degree of cluster homogeneity and is descriptive due to the construction of a tree for stepwise cluster merging: initially, each object is considered a separate cluster, then they are sequentially merged based on the selected proximity measure until only one remains. The algorithm terminates at a specified number of clusters, which is determined based on expert judgment.

To assess the reliability of the clustering results, the quality of the resulting cluster structure was additionally evaluated using within-cluster homogeneity and between-cluster differentiation as the main criteria. The analysis showed that the overall structure of the regional typology remained largely unchanged when the set of indicators was systematically varied, demonstrating the robustness of the proposed procedure. The results further suggested a clear differentiation between the identified groups of regions, thereby confirming the stability of the proposed classification. Ward's method was used to minimize within-cluster variance and produce highly homogeneous groups of regions. Overall, the reliability of the clustering results was supported by the theoretically grounded selection of indicators, their preliminary normalization, the application of Ward's method, and the robustness analysis of the resulting classification.

Based on a visual analysis of the dendrogram, seven clusters were selected, the largest of which includes 26 regions (Figure 1). The choice of 7 clusters is explained by a more homogeneous cluster and the development of 5 fairly large ones (with 11–26 objects per cluster). The remaining regions form the first four clusters, including 13, 11, 26, and 25 regions, respectively. The average values of the statistical indicators used for each cluster are presented in Table 2. Selecting a larger number of clusters leads to their disintegration and the development of small clusters-statistical outliers, and continuing the agglomeration process at the next step leads to the emergence of a "super-large" cluster of 34 regions and the remaining 7 clusters, consisting of 2–11 regions, which is generally less interpretable. This also confirmed the correctness of choosing 7 clusters. The final number of clusters was determined based on the analysis of the dendrogram, intercluster distances, and expert interpretation of the results, ensuring maximum internal homogeneity of the clusters and their meaningful interpretability.

Regions such as Murmansk Oblast, Magadan Oblast, the Republic of Khakassia, and Chukotka Autonomous Okrug represent three separate clusters that were added to the general hierarchical classification tree at the final steps. These regions differ significantly from the others in their low level of self-sufficiency in basic food products. At the same time, the affiliation of Murmansk Oblast (cluster 5) and Chukotka Autonomous Okrug (cluster 7) to the Arctic zone predetermines a high level of support for investment in fixed capital in agriculture and environmental protection. Magadan Oblast and the Republic of Khakassia (cluster 6) are regions recognized as unfavorable for agriculture. Extreme natural and climatic conditions act as a significant limiting factor for land use. In accordance with current legislation, producers are entitled to receive additional government support to offset production costs. Rural development in these regions is also financed at higher rates. The key performance principles of the agri-food systems in the four aforementioned regions are ensuring rural employment, improving living standards, and developing non-core activities.

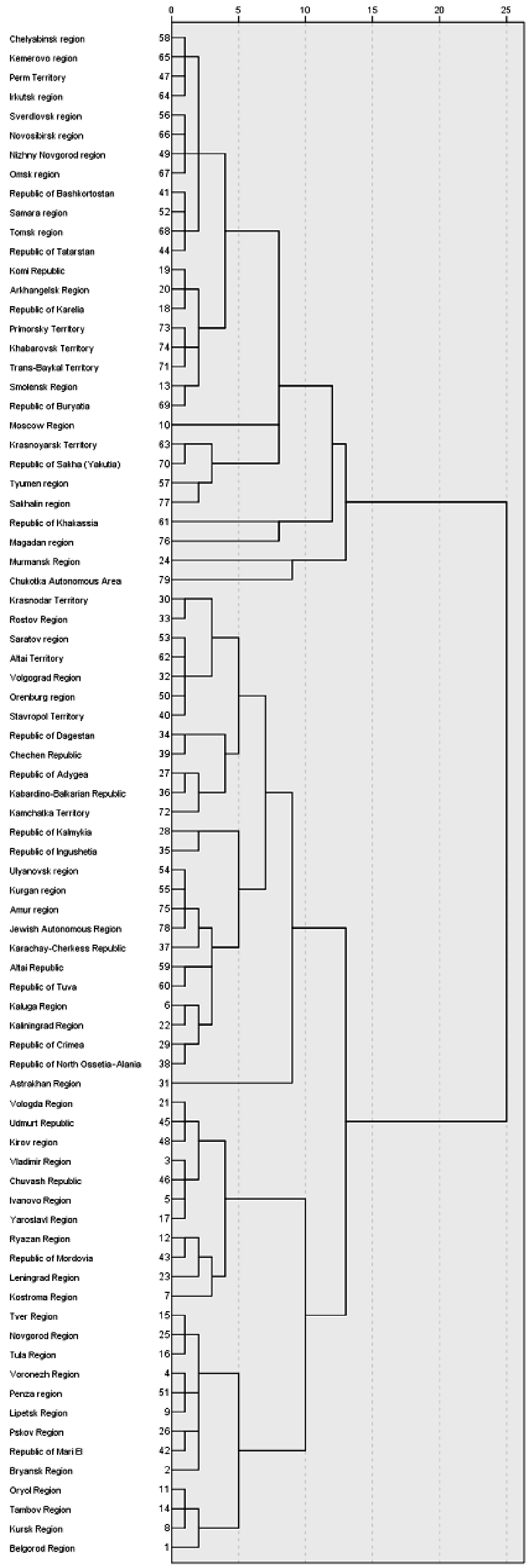

Figure 1. Hierarchical classification tree (dendrogram) constructed using Ward's method with the squared Euclidean distance as the main criterion.

A more detailed analysis was conducted for the first four clusters, as they were the most comparable across most indicators. The statistical data indicate that the first cluster is characterized by a combination of a high share of agriculture in gross regional product, high per capita agricultural output, and high levels of self-sufficiency in staple food products. This combination of indicators points to the development of an export-oriented agri-food system. At the same time, the cluster's comparatively weaker environmental performance indicates considerable pressure on natural resources, which constrains the system's long-term sustainability.

The first cluster is characterized by agricultural specialization, which is explained by the highest per capita agricultural production (141,300 rubles) and the share of agricultural output in the gross regional product (15.3%). This cluster includes such large agricultural regions—leaders in the production of oilseeds, pork, and poultry in the Central Federal District—as the Belgorod, Voronezh, Kursk, Lipetsk, Oryol, and Tambov Oblasts. The Mari El Republic is also among the largest pork and poultry-producing regions. The FSTP Sugar Beet Subprogram is being implemented in the Voronezh and Oryol Oblasts.

The cluster also boasts high economic stability in terms of agricultural enterprise profitability (77.0%). At the same time, labor productivity in agriculture (RUB 1,206,300) is lower than in the second and fourth clusters, and specific investment (RUB 5,587,600/ha) is significantly lower than in the fourth cluster. In terms of investment security, the Belgorod and Lipetsk regions stand out in the first cluster (RUB 8,836,900 and RUB 11,551,000, respectively), boasting high innovative potential in agricultural production. The SPIC (Agreement on the Protection and Promotion of Capital Investments) is widely used to support large investors in these regions. High food security is confirmed by self-sufficiency in meat and meat products, milk and dairy products, potatoes, vegetables, and melons. However, many social sustainability indicators are somewhat lower in the first cluster.

Reference [41] proposed a methodological approach to constructing an integrated indicator of quality of life, based on which a hierarchy of Russian regions was constructed. The threshold values of the integrated indicator indicate that the Belgorod Region is a leader (0.651), while the Kursk and Oryol Regions are among the laggards (0.420 and 0.436), respectively. The remaining 10 regions are characterized by an average quality of life. It should be noted that within the first cluster, there is a strong differentiation in the contribution of small businesses and peasant (farm) households. For example, with an average value of the share of turnover of small agricultural enterprises (5.3%), the share of small businesses in the Kursk Region was 10.4% in 2023, and in the Tambov Region–14.0%. The farming sector plays a particularly significant role in the Tula and Novgorod regions (15.0%), as well as in the Voronezh region (13.8%).

Substantial fluctuations in the per capita subsidy for integrated rural development are observed across all clusters, demonstrating varying opportunities for achieving social sustainability. Environmental sustainability indicators highlight existing challenges with waste disposal and treatment and the need to increase investment in environmental protection. Environmental issues are particularly significant for large pig farms in the Belgorod and Kursk regions, which have a high anthropogenic load. This is confirmed by the waste disposal and treatment rate of 20.7% in the Belgorod region and 9.9% in the Kursk region.

The second cluster is as compact as the first, primarily comprising regions of the Central and Volga Federal Districts. The cluster is characterized by a more balanced combination of economic, social, and environmental dimensions. The findings suggest that the sustainable development of this group of regions is driven not by the maximization of individual indicators, but by more harmonious interactions among the various components of the agri-food system. Profitability, investment, and labor productivity indicators are comparable with those of the first cluster; however, per capita agricultural production and the share of agricultural output in the gross regional product are significantly lower. Among the regions of the second cluster, the Leningrad Region is the leader in economic sustainability, as evidenced by investment and labor productivity indicators. In 2023, the region achieved the highest investment level among all Russian regions with an agricultural specialization (RUB 20,514.2 per hectare of agricultural land). A distinctive feature of the cluster is its inclusion of leading regions in milk production: the Vologda, Kirov, Leningrad, and Ryazan Regions and the Udmurt Republic are the top 20 milk-producing regions. It is also worth noting the dominance of the Leningrad, Ryazan, and Yaroslavl Regions and the Republic of Mordovia in the Russian egg market. The share of these regions in total production was 18.5%.

Accordingly, the second cluster has the highest self-sufficiency in milk and eggs. The presence of large livestock organizations explains the low share of small businesses and the farm sector in agricultural production, although a significant level of state support creates the conditions for the functioning of rural areas. For example, in the Leningrad Region, the level of state support per 1 hectare of agricultural land was 6044.8 rubles, with an average value for the regions in the cluster of 1555.3 rubles. Among the indicators of environmental sustainability, it is worth noting the higher level of waste recycling and disposal in the total volume of waste (77.5%) compared to other clusters.

The third and fourth clusters are the most numerous and are distributed across several territorial areas. The largest areas in the third cluster are the entire Southern and North Caucasus Federal Districts. The fourth cluster is dominated by the Volga Federal District (5 regions), the Siberian Federal District (6 regions), and the Far Eastern Federal District (6 regions). Furthermore, it is important to consider the inclusion in these clusters of 25 regions recognized as unfavorable for agriculture, with limited potential for economic growth in the agricultural sector.

For the third cluster, major constraints on sustainable development include low levels of investment in fixed capital and environmental protection, insufficient government support for agriculture, relatively low labor productivity, and limited diversification of agricultural production due to land constraints and the predominance of small-scale farming.

The third cluster boasts a relatively high share of profitable agricultural enterprises (76.5%); however, the ratio of fixed capital investment per hectare of agricultural land is 33% to 46% lower than in the first two clusters and the fourth cluster. The obvious outsiders are such regions unfavorable for agriculture as the Republic of Ingushetia (8.1 thousand rubles); the Republic of Tyva (12.4 thousand rubles); the Republic of Kalmykia (67.3 thousand rubles); the Altai Republic (71.9 thousand rubles). The cluster stands out for its highest food sustainability in terms of self-sufficiency in vegetables and melons (105.7%), which is explained by the corresponding specialization of the regions of the Southern and North Caucasian Federal Districts. For example, in the Astrakhan Region, self-sufficiency in vegetables and melons in 2023 amounted to 616.3%, and in the Volgograd Region, 258.0%. A significant part of the land fund of the regions of the North Caucasian Federal District is located in mountain ranges with unsatisfactory soil conditions. It should be noted that agricultural land is limited, and the small-scale nature of production, especially in livestock farming, complicates the diversification of agricultural production. The average land area of rural entrepreneurs is just over 9 hectares.

The analysis of the statistical indicators for the fourth cluster revealed a combination of a low share of agriculture in gross regional product, limited diversification of agricultural production, a low level of food self-sufficiency, and high investment potential, which serves as a key factor in enhancing the sustainability of the agri-food system.

The fourth cluster is characterized by a lower agricultural market capacity. Agricultural output accounts for 3.9% of the gross regional product, while per capita agricultural output is 35,200 rubles. The share of profitable farms is 8–9 percentage points lower than in the first three clusters, but labor productivity is 70–90% higher. Compared with the first three clusters, labor productivity fluctuates significantly. The highest labor productivity in agriculture was achieved in Krasnoyarsk Krai (2,364,900 rubles), as well as in Arkhangelsk, Sakhalin, and Tyumen Oblasts (2,590,200 rubles, 5,463,700 rubles, and 6,182,500 rubles, respectively). Environmental constraints due to the significantly small rural population and significant areas of specially protected rural areas in eight regions of the Siberian and Far Eastern Federal Districts result in lower agricultural specialization: the share of agricultural output in the gross regional product is approximately 4%; the ratio of agricultural output per capita is 2–4 times lower than in the first three clusters.

Overall, the fourth cluster faces problems with self-sufficiency in meat and meat products, milk and dairy products, and vegetables and melons. Furthermore, lower food availability complicates the problem of achieving food security. Rural development in Siberia and the Far East is characterized by the presence of small settlements and micro-settlements requiring essential social infrastructure. Higher values of achieved environmental sustainability indicators (especially investments in environmental protection) are largely explained by increased costs for the maintenance of specially protected areas and nature reserves [42].

At the same time, Novosibirsk Oblast, Primorsky Krai, and the Republic of Buryatia need to dramatically improve waste management and disposal. The share of waste management and disposal in total waste was 1.2%, 2.5%, and 13%, respectively.

The research revealed that environmental sustainability is not only an independent component but also a factor determining the long-term productivity of agri-food systems through the preservation of soil fertility, water resources, and ecosystem services. Sustainable development issues are particularly relevant for livestock farming, as this sector remains subject to relatively high risks of increasing anthropogenic pressure on the natural environment [43]. As in many countries worldwide, livestock farming activities in Russia have a negative impact on the environment, which is particularly characteristic of pig farming due to its high degree of concentration. The author's position is based on the need to assess the maximum permissible limits of production concentration that meet sustainable development requirements. Based on Lösch's conceptual approaches to the spatial organization of production [44], the limits of production concentration for individual types of livestock products are examined in accordance with sustainable development criteria such as economic growth, resource efficiency, and rational environmental management. An impact research of cow population concentration on the ecological and economic component of sustainable development showed that enterprises with a herd of over 2000 cows experience problems in maintaining ecological balance. The best indicators of efficiency and intensity of milk production were achieved in regions with a lower degree of production concentration [45].

Thus, the results of the cluster analysis confirm that different groups of regions require differentiated government support strategies tailored to their statistically identified development characteristics.

Considering the achieved sustainability indicators and the potential for further development of agricultural systems in accordance with socio-economic and environmental goals, the authors propose methodological approaches to developing priority areas (regional strategies) for sustainable development management for the relevant clusters (Appendix A).

5. Conclusions

The scientific contribution of this research is the use of cluster modeling methodology and tools to analyze the relationship between indicators of agricultural specialization, economic efficiency, food security, social and environmental sustainability, the development of tools for diagnosing the problem and improving mechanisms for managing the sustainable development of regional agri-food systems.

Using cluster analysis to study indicators of the functioning of Russia's agri-food systems, differences in the levels of economic, food, social, and environmental sustainability were identified across groups of selected regions, and priority areas for sustainable development for the corresponding clusters were substantiated. Environmental sustainability indicators highlight existing problems with waste disposal and neutralization and highlight the need to increase investment in environmental protection in virtually all clusters.

The author's recommendations for each cluster are presented below. The development of the first cluster is determined by agricultural specialization in the production of oilseeds, pork, and poultry. The stable financial position of commodity producers is explained by the dominance of large agricultural enterprises with high innovative potential and the effective support of major investors. The competitive advantages of pork and poultry production are associated with reduced feed and labor costs due to the scaling of production at innovative enterprises. It should be noted that these major companies fully comply with international standards in terms of their technical and technological development. Accordingly, the development of a domestic breeding base and the establishment of slaughterhouses and advanced processing facilities remain crucial for the sustainable development of the industry. Further development of the cluster will be determined by increasing meat and dairy production and establishing high-value-added agricultural export zones based on the implementation of an innovation and investment strategy aimed at implementing investment projects related to the digital economy. State support mechanisms for agricultural organizations must take into account the current innovative potential. The creation of technological platforms is a key area for stimulating innovative development in the agri-food sector. The increasing anthropogenic load on agricultural production necessitates the conceptual goal of adhering to the principles of rational nature management and achieving environmental safety. Positive environmental effects can be achieved by fostering environmentally responsible behavior among agribusiness entrepreneurs, taking into account industry specifics, and strengthening control over compliance with emission limits for large livestock farms.

In the second cluster, the development of production and processing is largely linked to both satisfying intraregional needs and improving interregional exchange, creating grain and meat and dairy export zones. Further enhancement of the innovative potential of dairy farming is possible through improved selection and genetics, maintaining a balanced diet, and implementing advanced cow management technologies. The transition of dairy farms to a fundamentally new technological foundation will facilitate the development of new interaction schemes between innovation participants and the more active use of new technologies in small businesses. Of significant importance is the development of mechanisms to stimulate an increase in the share of dairy products produced using innovative technologies. The authors' research has revealed an insufficient impact of innovation support on milk marketability and cow productivity. The development of beef cattle breeding is a promising area, as it helps address rural employment issues. A positive example of regional support for peasant (farm) households raising and fattening specialized beef breeds can be found in the Leningrad Region.

In the third cluster regions, it is necessary to increase the intensity of agricultural production in the face of land shortages. Improving the resource potential of small and medium-sized enterprises is associated with the organization of in-depth processing of livestock products, including through strategic cooperation with neighboring regions. According to the Dairy Market Research Center, disadvantaged regions of the North Caucasus macroregion (with the exception of the Karachay-Cherkess Republic) experience a significant shortage of milk processing capacity. It is possible to create a dairy cluster based on the raw materials of the Kabardino-Balkarian and Karachay-Cherkess Republics. A promising area is the development of intersectoral projects for agro-industrial production related to the food industry, the production of premium food products, and the development of rural areas and agricultural services, including rural tourism.

For the development of the fourth cluster, it is crucial to develop forms of cooperation between small, medium, and large businesses in the face of environmental and economic constraints. Another key constraint is the underdeveloped logistics infrastructure, including transport. Therefore, in these regions, it is preferable to expand their own feed base, primarily rapeseed and soybeans, as well as expand the export potential of rapeseed and soybeans, provided that processing facilities are expanded.

The study revealed that the task of attracting additional investment resources to upgrade the technological base of priority agricultural subsectors, as well as creating the necessary infrastructure and expanding processing capacity, remains pressing for most regions. This will improve the competitiveness of products and ensure sustainable economic growth [46]. This is consistent with modern scientific research on regional agri-food system sustainable development in the context of achieving food security. The annual growth rate of investment in fixed capital in agriculture in Russian regions should be at least 10% [47]. Increasing investment resources largely depends on the effectiveness of the investment lending system based on guarantees and collateral. There are interregional disparities in investment support, so there is a need to increase the level of interest rate subsidies on investment loans. Interregional differentiation in subsidies for reimbursing the costs of modernizing dairy farms leads to “pinpoint” leaps in modernization. Furthermore, most regions require measures to stimulate rural employment and model effective integration with agricultural and processing organizations.

The findings make it possible to move away from standardized government support instruments toward a cluster-oriented model for managing the sustainable development of agri-food systems.

Regions in the first cluster primarily require the environmental modernization of agricultural production and incentives for the adoption of resource-efficient technologies.

For regions in the second cluster, the main priority is to maintain the balance already achieved among economic growth, social sustainability, and the conservation of natural resources.

For regions in the third cluster, the most effective areas of government policy include increasing investment in agricultural fixed capital and environmentally sustainable practices, promoting greater production specialization by supporting the development of sheep and goat farming, and encouraging cooperation among small-scale farms. The estimates indicate that improving economic sustainability would require an 80–90% increase in investment in agricultural fixed capital, while improving social sustainability would require a 50–60% increase in government support for agriculture.

For regions in the fourth cluster, the most effective areas of government policy include developing transport infrastructure, expanding investment support, promoting cooperation among small-scale farms, and modernizing food-processing facilities. More efficient use of crop production potential requires greater diversification through a 5–10% expansion of the area under soybean and rapeseed cultivation. Increasing self-sufficiency in meat and meat products requires the establishment of specialized beef-cattle production zones, with government funding provided for the necessary infrastructure.

Thus, the proposed typology provides a basis for developing targeted government support measures informed by the results of the statistical analysis.

Based on the results of the research, regions in all cluster groups are recommended to ensure conditions for enhancing the innovative activity of agricultural organizations by more actively attracting investment resources for the development of production facilities engaged in the deep processing of raw materials. To ensure targeted government support measures, it is advisable to use tools such as subsidized investment loans; incentives for agricultural producers to purchase highly innovative machinery and equipment; and partial reimbursement of direct costs for the construction and modernization of facilities. It is also necessary to develop measures to establish and develop systemic food import substitution chains, including the link between the technological base for raw material production, its comprehensive processing, and effective distribution, as well as logistics.

Stimulating sustainable technological development in the agro-industrial complex requires the implementation of an active state innovation policy, which should be aimed at creating conditions for the effective development of innovation and the further formation of development institutions (technology parks, venture funds, business incubators, etc.), as well as enshrining these principles at the legislative level. Investment support mechanisms should stimulate the dissemination of innovation across industries and product chains, with the use of fundamentally new forms of financing innovative businesses being crucial: grants, international programs, fundraising, crowd sourcing, crowd funding, ICOs, and venture capital investments. One way to stimulate regional investment activity could be to grant regions of the Russian Federation autonomy in identifying opportunities to reduce investment barriers, formulating and providing incentives, and selecting promising areas of economic activity.

Limitations. In our opinion, the obtained results should be considered critically, as they may be due to objective limitations of both the primary statistical data used to calculate indicators and construct econometric models, and the chosen research methodology, including a high degree of primary data aggregation for interregional comparisons; a lack of reliable estimates for the indicators used in the first years of statistical observation; and limitations of statistical information on a number of environmental and food sustainability indicators at the regional level, which requires additional surveys.

In our opinion, it is necessary to develop and implement more detailed statistical reporting forms and regularly publish detailed data on environmental activities in agriculture at the regional level (soil degradation indicators, nutrient balance, water pollution, greenhouse gas emissions from agricultural activities, etc.).

Further research activities envisage expanding the range of environmental indicators to include land degradation, pesticide and water consumption per unit of production, and greenhouse gas emissions from agricultural activities. This will require additional data collection in pilot regions and individual farms. The proposed methodology will be developed using Principal Component Analysis (PCA) method and subsequent economic and mathematical modeling of the relationships between the variables under research.

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Appendix A

Table A1. Priority Areas for Sustainable Development of Regional Agro-food Systems.

Cluster Names	Priority Areas (Strategies) for Sustainable Development of Regional Ecosystems	Mechanisms for Sustainable Development
Cluster 1	Economic Sustainability Innovative Structural Shifts in Livestock Production and Processing	Stimulating the implementation of technological innovations in meat and dairy production; creating technological platforms. New models for interaction between innovation participants and more active use of new technologies in small businesses. Using new forms of financing for innovative businesses.
	Food Sustainability Development of commodity resources in high-value-added meat and dairy export zones	Diversification of export structures based on increased production and processing of meat and dairy products
	Social sustainability	Developing the innovative potential of the workforce and their acquisition of new digital economy competencies
	Environmental Sustainability Compliance with principles of rational environmental management and achieving environmental safety	Encouraging environmentally responsible behavior by agribusiness entrepreneurs, taking into account industry-specific characteristics, as well as enhanced monitoring of compliance with emission limits for large livestock complexes
Cluster 2	Economic Sustainability Achieving economic growth in the dairy sector through innovative factors with a goal of sustainable environmental management. Increasing the innovative potential of milk production and processing through selective breeding and genetic work, achieving feed balance and optimization of dairy herd management technology, and advanced milk processing. Expanding the area of natural forage lands, taking into account the potential increase in beef cattle numbers	Mechanisms for incentivizing an increase in the share of dairy products produced using innovative technologies. Stimulating the dissemination of innovations across industries and product chains.
	Food Sustainability Development of interregional food exchanges	Stimulating effective interregional interactions in the milk and meat markets
	Social sustainability	Building the innovative potential of the workforce and developing new digital economy competencies
	Environmental Sustainability Implementation of principles of rational environmental management	Encouraging environmentally responsible behavior by agribusiness entrepreneurs, taking into account industry-specific characteristics, as well as strengthening monitoring of compliance with emission limits for large livestock farms. Encouraging the reclamation of unused land. Implementing measures to preserve soil fertility
Cluster 3	Economic sustainability Increasing the intensity of agricultural production in land-poor conditions by increasing livestock production in the small-scale sector	Supporting sheep and goat farming on household farms, encouraging beef cattle breeding on peasant farms, and promoting cooperation. Developing optimal production strategies for the development and modernization of the dairy goat industry, and strengthening state support for goat milk producer
	Food Sustainability Import Substitution Strategy by Increasing Milk Production in the Small-Scale Sector Development of functional food markets based on goat milk processing to meet the population's needs for dietary and hypoallergenic dairy products	Creating conditions for more complete use of raw materials on the basis of interregional cooperation
	Social sustainability Development of the rural environment and rural territories based on increasing the level of employment of the population and their acquisition of new competencies	Developing a system of uniform spatial settlement. Providing rural areas with transport, energy, and information infrastructure
	Environmental Sustainability Maintaining Ecological Balance in Regional Agri-Food Systems	Measures to organize pasture management and preserve soil fertility. Development of regional pasture restoration programs, stimulation of the reclamation of unused lands. Increased investment in environmental protection

Table A1. *Cont.*

Cluster Names	Priority Areas (Strategies) for Sustainable Development of Regional Ecosystems	Mechanisms for Sustainable Development
Cluster 4	Economic Sustainability Expansion of natural grassland areas for the development of dairy and beef cattle farming. Creation of large-scale pasture areas for raising beef cattle. In-depth processing of meat and dairy products, formation of beef cattle development clusters and large companies with a closed production cycle. Organic agricultural production using innovative agrobiotechnology	Support for the development of dairy and beef cattle farming in small businesses. Investment in beef cattle farming infrastructure; establishment of mutually beneficial relationships between small agricultural businesses and meat processing plants; provision of bank loans and credits to small businesses. Subsidies for organic production include partial reimbursement of costs for the cultivation of grain, legumes, and forage crops; cattle raising; the purchase of biological control agents; veterinary drugs; and feed additives
	Food Sustainability Diversification of export structures through increased production and processing of cattle meat, rapeseed, and soybeans in the Siberian and Far Eastern Federal Districts	Provision of regional subsidies for rapeseed and soybean production.
	Social sustainability Development of rural areas based on increasing rural employment through economic diversification, expansion of agricultural processing, development of traditional industries and tourism	Expanding government support for local producers to address social issues related to rural development. Supporting traditional lifestyles and improving micro-settlements using autonomous energy systems
	Environmental sustainability Maintaining ecological balance in regional agri-food systems	Stimulating the inclusion of unused lands into circulation, ensuring control over the state of specially protected areas and reserves

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