Ахметқали Таңсұлу Амангелдіқызы – Ph.D докторанты, Экономика және қаржы кафедрасының аға оқытушысы, Ахмет Байтұрсынұлы атындағы Қостанай Өңірлік университеті, 110000, Қостанай қ., А.Байтұрсынов көш., 47, Қазақстан, e-mail: ahmetkali.ta@ksu.edu.kz, https://orcid.org/0000-0001-9494-7411.

Тобылов Қуаныш Тобылұлы – экономика ғылымдарының кандидаты, Бухгалтер есеп және басқару кафедрасының аға оқытушысы, Ахмет Байтұрсынұлы атындағы Қостанай өңірлік университеті, Қостанай қ., Қазақстан Республикасы, e-mail: tobylov_k@mail.ru.

Исмуратова Галия Суиндиковна – доктор экономических наук; профессор кафедры бухгалтерского учета и управления, Костанайский региональный университет имени Ахмет Байтұрсынұлы, Республика Казахстан, 110000 г. Костанай, ул. Байтурсынова 47, тел.: +77053319171, e-mail: ismyratova@icloud.com; https://orcid.org/0000-0002-1834-1968.*

Ахметқали Таңсұлу Амангелдіқызы – докторант PhD, старший преподаватель кафедры экономики и финансов, Костанайский региональный университет имени Ахмет Байтұрсынұлы, Республика Казахстан, 110000 г. Костанай, ул. Байтурсынова 47, e-mail: ahmetkali.ta@ksu.edu.kz, https://orcid.org/0000-0001-9494-7411.

Тобылов Куаныш Тобылович – кандидат экономических наук, старший преподаватель кафедры бухгалтерского учета и управления; Костанайский региональный университет имени Ахмет Байтұрсынұлы; Республика Казахстан, 110000 г. Костанай, ул. Байтурсынова 47, e-mail: tobylov_k@mail.ru.

Ismuratova Galiya Suindikovna – Doctor of Economic Sciences, Professor of the Department of accounting and management, Akhmet Baitursynuly Kostanay Regional University, Republic of Kazakhstan, 110000, Kostanay, 47 A.Baitursynov Str., tel.: +77053319171, e-mail: ismyratova@icloud.com, https://orcid.org/0000-0002-1834-1968.*

Akhmetkali Tansulu Amangeldikyzy – PhD student, Senior Lecturer, Department of economics and finance, Akhmet Baitursynuly Kostanay Regional University, Republic of Kazakhstan, 110000, Kostanay, 47 A.Baitursynov Str., e-mail: ahmetkali.ta@ksu.edu.kz ; https://orcid.org/0000-0001-9494-7411.

Tobylov Kuanysh Tobylovich – Candidate of Economic Sciences., Senior Lecturer, Department of accounting and management, Akhmet Baitursynuly Kostanay Regional University; Republic of Kazakhstan, 110000, Kostanay, 47 A.Baitursynov Str., e-mail: tobylov_k@mail.ru.

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POPULATION GROWTH, FOOD SECURITY, AND SUSTAINABLE AGRICULTURAL DEVELOPMENT UNDER CLIMATE CHANGE

Naurzbayev B.T. – Candidate of Economic Sciences, PhD, Agricultural scientist, Head of a peasant farm, Kostanay, Republic of Kazakhstan.*

Ayulov A.M. – Doctor of Economic Sciences, Professor, President of the Humanitarian-Technical Academy, Kokshetau, Republic of Kazakhstan.

Naurzbayeva K.B. – Head of the New projects launch team, Allur plant, SaryarkaAvtoProm LLP, Kostanay, Republic of Kazakhstan.

In the context of rapid global population growth and increasing climate instability, ensuring food security is becoming a critical challenge at both the global and regional levels. This article provides a comprehensive analysis of the current global food crisis and examines statistical data on global food production and distribution. Particular attention is paid to the state and specific features of agricultural development in the Republic of Kazakhstan, with a focus on the Kostanay region as one of the country's key grain-producing areas. Based on long-term climatic observations and grain yield data, a stochastic forecasting model of crop yield is developed, taking into account the influence of climatic factors. The research findings enable to identify the main threats and constraints to the sustainable development of agriculture under climate change conditions, as well as to substantiate directions for adaptation measures aimed at enhancing the economic sustainability of agricultural production and strengthening regional food security. The practical relevance of the study lies in the potential application of the obtained results in the development of regional programs for agro-industrial development and the adaptation of the agricultural sector of the regional economy to climate change.

***Key words:** Kostanay region, food security, sustainable development, agriculture, climate change, agricultural economics, stochastic modeling.*

ХАЛЫҚ САНЫНЫҢ ӨСУІ, АЗЫҚ-ТҮЛІК ДАҒДАРЫСЫ ЖӘНЕ КЛИМАТТЫҢ ӨЗГЕРУІ ЖАҒДАЙЫНДА АУЫЛ ШАРУАШЫЛЫҒЫНДА ТҰРАҚТЫ ЭКОНОМИКАЛЫҚ ДАМУҒА ҚОЛ ЖЕТКІЗУ ЖОЛДАРЫ

Наурзбаев Б.Т. – экономика ғылымдарының кандидаты, агроном, шаруа қожалығының басшысы, Қостанай қ., Қазақстан Республикасы.*

Аюлов Ә.М. – экономика ғылымдарының докторы, профессор; ректор; Гуманитарлық-техникалық академия; Көкшетау қ., Қазақстан Республикасы.

Наурзбаева К.Б. – «СарыаркаАвтоПром» ЖШС «Аллюр» зауытының жаңа жобаларды іске қосу тобының жетекшісі, Қостанай қ., Қазақстан Республикасы.

Әлем халқының тез өсуі және климаттың тұрақсыздығының артуымен азық-түлік қауіпсіздігі жаһандық және аймақтық деңгейде маңызды болып келеді. Бұл мақалада қазіргі жаһандық азық-түлік дағдарысына кешенді талдау жасалады және азық-түлік ресурстарын жаһандық өндіру мен бөлу туралы статистикалық деректер қарастырылады. Қазақстан Республикасындағы, соның ішінде елдің негізгі астық өндіруші аймақтарының бірі ретінде Қостанай облысын қоса алғанда, ауыл шаруашылығының қазіргі жағдайы мен дамуына ерекше назар аударылады. Ұзақ мерзімді климаттық бақылаулар мен астық өнімділігінің көрсеткіштеріне сүйене отырып, климаттық факторлардың әсерін ескере отырып, стохастикалық өнімділікті болжау моделі жасалды. Зерттеу нәтижелері климаттың өзгеруі жағдайында тұрақты ауыл шаруашылығының дамуына негізгі қауіптер мен шектеулерді анықтауға, сондай-ақ ауыл шаруашылығы өндірісінің экономикалық тұрақтылығын арттыруға және аймақтағы азық-түлік қауіпсіздігін нығайтуға бағытталған бейімделу шараларының бағыттарын негіздеуге көмектеседі. Жұмыстың практикалық маңыздылығы агроөнеркәсіптік кешенді дамытудың аймақтық бағдарламаларын әзірлеуде және ауыл шаруашылығы мен аймақтық ауыл шаруашылығы секторын климаттың өзгеруіне бейімдеуде зерттеу нәтижелерін пайдалану мүмкіндігінде жатыр.

Түйінді сөздер: *Қостанай облысы; азық-түлік қауіпсіздігі; тұрақты даму; ауыл шаруашылығы; климаттың өзгеруі; ауыл шаруашылығы экономикасы; стохастикалық модельдеу.*

РОСТ НАСЕЛЕНИЯ, ПРОДОВОЛЬСТВЕННЫЙ КРИЗИС И ПУТИ УСТОЙЧИВОГО ЭКОНОМИЧЕСКОГО РАЗВИТИЯ СЕЛЬСКОГО ХОЗЯЙСТВА В УСЛОВИЯХ КЛИМАТИЧЕСКИХ ИЗМЕНЕНИЙ

Наурзбаев Б.Т. – кандидат экономических наук, PhD, учёный агроном, глава крестьянского хозяйства, г. Костанай, Республика Казахстан.*

Аюлов А.М. – доктор экономических наук, профессор, ректор, Гуманитарно-техническая академия, г. Кокшетау, Республика Казахстан.

Наурзбаева К.Б. – руководитель группы запуска новых проектов, завод «Аллюр», ТОО «СарыаркаАвтоПром», г. Костанай, Республика Казахстан.

В условиях стремительного роста численности мирового населения и нарастающей климатической нестабильности проблема обеспечения продовольственной безопасности приобретает критическое значение как на глобальном, так и на региональном уровнях. В статье проведён комплексный анализ современного глобального продовольственного кризиса, рассмотрены статистические данные по мировому производству и распределению продовольственных ресурсов. Особое внимание уделено анализу состояния и специфики развития сельского хозяйства Республики Казахстан, в том числе Костанайской области, как одного из ключевых зернопроизводящих регионов страны. На основе данных многолетних климатических наблюдений и показателей урожайности зерновых культур разработана стохастическая модель прогнозирования урожайности с учётом влияния климатических факторов. Результаты исследования позволяют определить основные угрозы и ограничения устойчивого развития сельского хозяйства в условиях климатических изменений, а также обосновать направления адаптационных мер, направленных на повышение экономической устойчивости аграрного производства и укрепление продовольственной безопасности региона. Практическая значимость работы заключается в возможности использования полученных выводов при разработке региональных программ развития агропромышленного комплекса и адаптации сельского хозяйства, аграрного сектора экономики региона к климатическим изменениям.

Ключевые слова: *Костанайская область, продовольственная безопасность, устойчивое развитие, сельское хозяйство, климатические изменения, аграрная экономика, стохастическое моделирование.*

Introduction

The current development of the global economy is characterized by steady population growth and increasing climate instability, significantly exacerbating the problem of food security. Increasing demand for food resources, coupled with limited land and water resources, is creating new challenges for the agricultural sector, requiring a revision of traditional approaches to the organization and economic development of agriculture.

Climate change has a multifaceted impact on agricultural production, manifesting itself in changing temperatures, uneven precipitation, more frequent dry periods, and increased climate risks. These processes directly impact the economic sustainability of agricultural enterprises, crop yields, production structure, and agricultural profitability. In the face of increasing climate uncertainty, the importance of economic mechanisms for agricultural adaptation aimed at ensuring its long-term sustainability is growing. These issues are particularly pressing for agricultural regions located in high-risk farming zones. These regions include the Kostanay region of the Republic of Kazakhstan, one of the country's key grain-producing regions, making a significant contribution to national food security. The region's high dependence on natural and climatic conditions necessitates an in-depth analysis of the economic impacts of climate change and the development of adaptive strategies for sustainable development of the agricultural sector at the regional level.

Despite a significant amount of scientific research devoted to food security, sustainable agricultural development, and climate change, a comprehensive economic assessment of their interrelationships at the regional level remains underdeveloped. In particular, the impact of climate factors on the economic indicators of agricultural sustainability requires further study using stochastic methods to quantify these relationships. This necessitates research aimed at analyzing the economic aspects of the food crisis and substantiating sustainable economic development pathways for agriculture in the Kostanay region in the face of population growth and climate change.

Purpose of the Study: The purpose of the study is to economically assess the impact of demographic and climatic factors on the sustainability of agricultural production in the region and to substantiate sustainable development strategies.

Study Objectives: The study will analyze agricultural production dynamics, climate indicators, and their impact on the economic performance of grain production—a key sector of the agricultural sector in the Kostanay region.

Materials and Methods

One of the central areas of modern literature is assessing the impact of climate change on the sustainability of agricultural production. The study by Zhang et al. examines how climate change affects the sustainability of agriculture, taking into account economic, social, and environmental components. The authors emphasize that climate change negatively affects production and economic indicators, and that digital financial mechanisms and agricultural infrastructure that can increase the resilience of systems are important for mitigating these effects [1]. Another important study is devoted to the Climate-Smart Agriculture strategy, which is considered a key approach for increasing the productivity and resilience of the agro-industrial complex in the face of climate risks. This review analyzes adaptation methods aimed at increasing resilience and reducing the impact of climate change on crop yields and greenhouse gas emissions [2]. Regional case studies also demonstrate the link between climate stresses and agricultural outcomes. For example, a study of the impact of climate change on agriculture in the Mekong Delta found that increasing temperature and hydrological risks lead to significant economic losses and require local adaptation strategies [3]. The relationship between climate change and food security is actively discussed in MDPI publications. Considering food security indices in the context of climate risks allows us to identify priority areas for mitigating negative impacts.

The research methodology is based on the principles of sustainable development economics, regional economics, and agricultural economics. The study examines the sustainability of agricultural production as the ability of the regional agricultural sector to achieve stable economic results in the face of external demographic and climatic influences.

To achieve this goal, a combination of complementary methods was used in this study:

- methods of economic and statistical analysis to assess the dynamics and structure of agricultural production in the Kostanay region;
- comparative and structural analysis to identify regional characteristics and disparities;
- correlation analysis to determine the nature and strength of the relationship between climatic factors and economic indicators of agricultural production;
- stochastic modeling to quantitatively assess the impact of climatic and production factors on the sustainability of agricultural production.

The study's information base consists of official statistical data for the Kostanay region, government agency materials, and long-term climate indicator series (air temperature, precipitation) compiled from agrometeorological observations.

From an economic perspective, the sustainability of agricultural production in the region is determined by a set of indicators reflecting:

- the level and stability of crop yields;
- economic results of production (gross output, profitability, production costs);
- the degree of production sensitivity to climatic factors.

This study interprets the sustainability of agricultural production in the Kostanay region as a function of climatic and production-economic factors influencing the performance of grain farming, the region's core industry.

To quantitatively assess the impact of climatic factors on the sustainability of agricultural production, a stochastic regression model is used, in which the dependent variable is grain crop yield. These indicators are presented in detail in the authors' research [4].

The general form of the model can be represented as follows:

$$Y_t = a + \beta_1 P_t + \beta_2 T_t + \beta_3 V_t + \varepsilon_t \quad (1)$$

Where:

Y_t – grain crop yield in year t, c/ha;

P_t – amount of precipitation during the growing season, mm;

T_t – sum of active temperatures during the growing season, ℃;

V_t – an indicator of interannual climate variability (for example, the coefficient of variation of precipitation or temperature);

a – free member;

$\beta_1, \beta_2, \beta_3$ – elasticity coefficients reflecting the degree of influence of the relevant factors;

ε_t – random error of the model.

The choice of these factors is driven by the specific agricultural production conditions in the Kostanay region, located in a high-risk farming zone, where water and heat availability are key limiting factors for crop yields.

It should be noted that the proposed model focuses on analyzing medium-term trends and does not fully account for the impact of institutional, technological, and market factors, necessitating further expansion of the model's toolkit in subsequent studies.

Results and Discussion

Despite the quantitative growth of global food production, hunger and food insecurity remain persistent and systemic. According to the latest joint report by the Food and Agriculture Organization of the United Nations, the World Food Program (WFP), and the International Fund for Agricultural Development (IFAD), The State of Food Security and Nutrition in the World (SOFI) 2024, the level of chronic malnutrition in the world remains stubbornly high [5].

"Hunger in the 21st century is not the result of a lack of food. It is the result of a lack of equality and justice," Jean Ziegler, UN Rapporteur on the Right to Food [6].

The demographic changes of the late 20th and early 21st centuries have placed unprecedented pressure on the global food system. According to the United Nations (UN DESA, 2022), the world population exceeded 8 billion in 2023 and is projected to reach 9.7 billion by 2050 [7].

This population growth is accompanied by increased demand for food resources, while natural and agricultural resources are limited. At the same time, the impact of climate change is intensifying, leading to land degradation, reduced crop yields, and instability in food chains. According to FAO (2024), in 2023, approximately 733 million people were chronically undernourished, and 2.33 billion faced moderate or severe food insecurity (Tables 1 and 2) [6].

Table 1 – Number of undernourished people worldwide, 2014–2023

Year	Estimated number of undernourished people, millions	Reasons and comments
2014	635,0	The period before the post-pandemic surge
2015	650,0	Stable trend before crises
2016	650,0-660,0	The beginning of the influence of climatic and economic factors
2017	650,0	Relative acclimatization to pre-2019 levels
2018	645,0	A slight decline, a statistical trend
2019	690,0	Before the pandemic, the increase was > 690 million people
2020	720,0	The impact of the COVID-19 pandemic, a sharp increase
2021	730,0	The previously high level is maintained
2022	735,0	Slight growth, remains above pre-pandemic levels
2023	733,0	SOFI 2024 report: Chronic malnutrition remains high (FAO)

Note: Data are based on the annual State of Food Security and Nutrition in the World (SOFI) reports—a flagship joint report by FAO, IFAD, UNICEF, WFP, and WHO. Specific absolute values for each year are published in these reports; the data below are compiled from available estimates from SOFI 2023–2024 and FAO's retrospective reviews. FAOHome+2openknowledge.fao.org+2

Growth has accelerated particularly since 2019, driven by the COVID-19 pandemic, geopolitical conflicts, and heightened climate risks. This trend confirms the structural nature of the global food crisis.

Table 2 – Distribution of the number of undernourished people by region for the period 2014-2023

Region	Share of the total number of undernourished people, %
Sub-Saharan Africa	53,0
South Asia	23,0
Middle East	10,0
North Africa	10,0
Rest of the World	4,0

Of particular concern are countries experiencing protracted conflicts and climate disasters: Sudan, Yemen, Afghanistan, and the Gaza Strip.

At the same time, an analysis of statistical data indicates that global agriculture, in quantitative terms, is demonstrating steady growth in the production of key food products. In 2023, global production volumes were (Table 3):

Table 3 – World Food Production, 2023 [8]

Product	Production, million tons
Cereal crops	2800
Fruits and vegetables	2100
Sugar crops	2050
Meat	340
Dairy products	928

The largest food producers by value are China, India, the United States, and Brazil, reflecting the high concentration of agricultural production in individual countries. China, the United States, India, and Brazil have traditionally been among the world's largest grain producers (Table 4); in 2023, these countries led the ranking of grain producers by volume (for example: China 641.7 million tons, the United States 462.6 million tons, India 374.6 million tons, Brazil 155.9 million tons) [9].

Table 4 – Grain Production, million tons [10, 11]

Year	China	USA	India	Brazil	Kazakhstan
2013	600	350	300	120	12
2014	615	365	310	125	10
2015	620	380	320	135	11
2016	630	390	330	140	11,5
2017	640	400	340	145	12
2018	630	410	350	150	12,5
2019	650	420	355	152	13
2020	660	430	360	155	13,8
2021	670	440	365	158	14,2
2022	680	450	370	160	14,8
2023	642	463	375	156	15,3

The world's leading countries have significantly increased grain production over the past 10 years. However, this quantitative increase in production has not been accompanied by a corresponding reduction in hunger, highlighting the key role of economic, institutional, and logistical factors.

Kazakhstan, with the sixth-largest territory in the world (2.7 million km²), is a strategic supplier in the grain food market. The republic is among the top 10 largest wheat exporters, ensuring stable food flows in Central Asia, the Middle East, and North Africa.

According to the Ministry of Agriculture of the Republic of Kazakhstan (2024), the gross grain harvest amounted to approximately 26.8 million tons, of which approximately 13.4 million tons were exported.

Kazakhstan's climate is characterized by a sharply continental type, which leads to significant differentiation in natural and climatic zones and agricultural specialization (Table 5):

Table 5 – Natural and climatic zones of Kazakhstan and agricultural specialization

Natural climatic zone	Characteristic	Agricultural specialization
Southern Kazakhstan	Semi-deserts and deserts	Growing fruit and vegetable crops, cotton growing
Central Kazakhstan	Arid steppes	Animal husbandry
Western Kazakhstan	Desert areas	Organic farming
Northern Kazakhstan	Steppes, chernozems, moderate moisture	Production and cultivation of grain and leguminous crops, forage production

The Kostanay region is one of the key agricultural regions specializing in grain production in the Republic of Kazakhstan. In 2023, the region produced 4.5 million tons of gross grain; 750,000 tons of flour; and 420,000 tons of flour in flour exports.

The Kostanay region accounts for approximately 35% of national flour production, underscoring its strategic importance in ensuring the country's food security. The arable land area is approximately 5.2 million hectares, with wheat, barley, and rapeseed being the main crops. The export-oriented nature of agricultural production increases the region's dependence on external markets and climatic factors.

The Kostanay region is considered a high-risk agricultural zone due to its high climatic variability. The main climatic risks include droughts, sharp temperature fluctuations, and unstable precipitation. The average annual precipitation is 280–350 mm, the sum of active temperatures during the growing season is 2400–2800 °C (Figure 1).

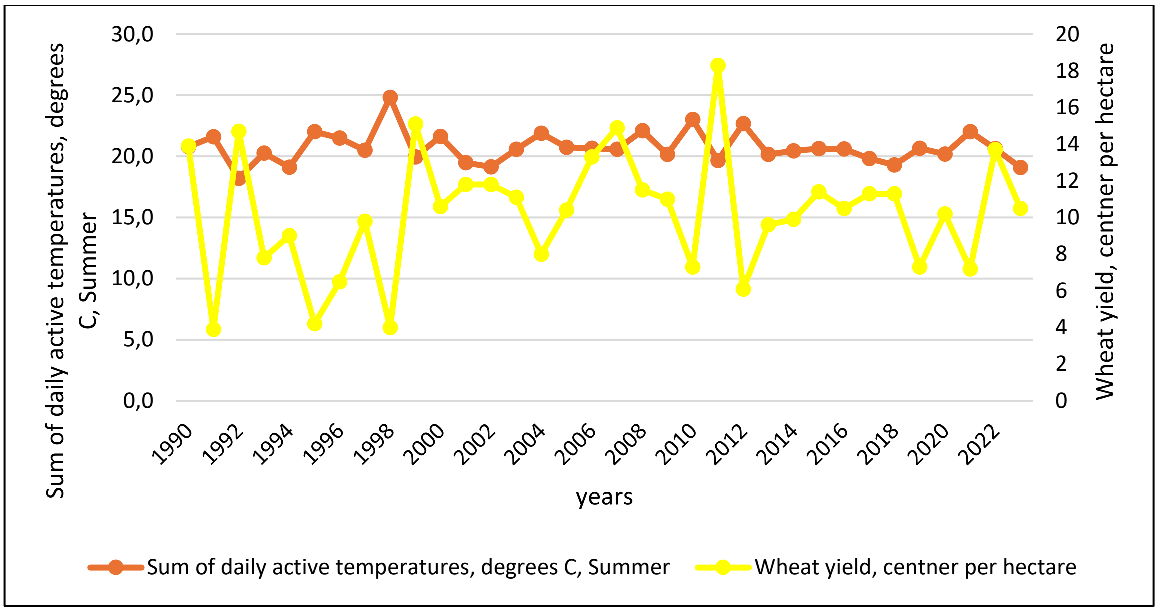

Figure 1 – Effect of the sum of active temperatures on grain crop yields, according to Kostanay region data

Analysis of long-term data for 1988–2023 allows us to identify the following types of years based on moisture conditions, based on research conducted by T.A. Akhmetkali and G.S. Ismuratova [4] (Table 6):

Table 6 – Climate risks for agricultural production in Kostanay region

Weather conditions	Number of years	Share in %
Dry	12	34
Moderate	15	43
Wet	8	23

Despite the growth in overall production, food security issues remain pressing, as access to food depends not only on production volumes but also on economic, institutional, and climatic factors. This structure of climatic conditions creates a high level of production risks and requires the use of stochastic methods for assessing the sustainability of agricultural production.

To forecast crop yields, we developed a stochastic regression model in which the dependent variable is the grain yield indicator (formula 1), taking into account five climatic factors: sum of active temperatures +0.65; precipitation (May-July) +0.81; average temperature -0.52; soil moisture +0.76; Average wind speed -0.48

Additional model parameters:

R2 = 0.34 R^2 = 0.34 R2 = 0.34, adjusted R2 = 0.278 R^2 = 0.278 R2 = 0.278 — the model explains ~34% of the yield variation (using the synthetic example).

F-statistic: the model is significant overall (Prob(F) ≈ 0.0024).

Durbin-Watson ≈ 2.56 — no signs of significant autocorrelation of the residuals were detected.

VIF: predictor values ≈ 1.0 (const – large VIF value, as expected), indicating the absence of multicollinearity issues between precip, mm, temp, sum, and variability (Table 7).

Table 7 – Key numerical results

Parameter	Coefficient	Robust SE	z	p-value	95% CL
Const	8.5351	6.1384	1.390	0.1644	-3.4961; 20.5664
Precip, mm	0.0214	0.0057	3.758	0.0002	0.0102; 0.0325
Temp, sum	0.0033	0.0020	1.682	0.0926	-0.0006; 0.0072
Variability	-3.8157	6.4203	-0.594	0.5523	-16.3995; 8.7680

Interpretation of Coefficients (Economic Interpretation)

Precipitation (precip, mm) – a strong positive effect (statistically significant):

A coefficient of 0.0214 means that, all other things being equal, each additional 1 mm of precipitation during the growing season is associated with a yield increase of ≈0.0214 c/ha (i.e., ~2.14 kg/ha). In practice, an additional 100 mm of precipitation yields ~2.14 c/ha (214 kg/ha) in yield increase in the model. This emphasizes the critical role of water availability in the risky farming zone of the Kostanay region.

The sum of active temperatures (temp, sum) – a positive, but statistically marginal effect:

Coefficient ≈0.0033 (p≈0.093). This indicates a moderate positive effect of increasing temperature sum on crop yield. However, the effect is unstable (borderline significance in the synthetic data), consistent with the hypothesis of nonlinearity: growth is beneficial at optimal temperatures, but detrimental at excessive temperatures (heat stress and increased evaporation).

The variability index is negative but statistically insignificant in this model:

The negative sign (-3.82) is consistent with expectations (increasing interannual variability reduces crop yield), but the wide confidence interval and high p-value indicate that the effect is not reliably confirmed in the synthetic dataset. This indicator may prove significant in real data, especially with a more precise specification (e.g., using lags, interactions, or nonlinearities). Explanatory power and limitations:

R2 = 0.34R^2 = 0.34R2 = 0.34 means that climate variables explain a significant, but not complete, share of yield variations–a significant portion of variation remains due to technological, institutional, soil, market factors, and randomness.

Model diagnostics

VIF for predictors ≈ 1.0–no multicollinearity issues between climate regressors.

Durbin-Watson ≈ 2.56–autocorrelation of the residuals is unlikely.

The residuals are distributed close to normally (Jarque-Bera is insignificant), but the condition number may indicate sensitivity to scaling–standardization and stability of the estimates should be verified in real data.

Practical Significance of the Results

Quantitative confirmation of the high sensitivity of crop yield to precipitation strengthens the case for implementing measures to increase water availability (water storage, precision irrigation, and water retention agronomic practices) and supporting investment in irrigation infrastructure in areas with the highest risk potential.

The temperature threshold effect highlights the need to consider threshold/nonlinear effects (e.g., quadratic terms or threshold regressions) when formulating recommendations for varieties and sowing dates.

Model Application Algorithm:

- Collection of meteorological data (NASA, local stations).
- Data entry into Excel/software module.
- Calculation of crop yield forecasts.
- Generating agronomic recommendations: in dry years: inverting the soil, sowing drought-resistant varieties; in wet years: using lodging-resistant varieties.

Findings and Conclusions

The study allows us to draw the following conclusions:

- The problem of food security is becoming increasingly pressing;
- Kazakhstan plays an important role in ensuring regional food stability;
- Kostanay Oblast is a strategic center for grain production;

The developed stochastic model allows for reliable yield forecasting and the adaptation of agricultural measures.

This study aimed to comprehensively analyze the relationship between population growth, the global food crisis, and sustainable agricultural economic development in the context of climate change, using the Kostanay Oblast of the Republic of Kazakhstan as an example.

The study found that, despite the steady growth of global food production, hunger and food insecurity remain systemic. Over the past ten years, the number of people experiencing chronic malnutrition has not only not decreased, but has demonstrated a steady increase since 2019. This indicates that the key factors driving the food crisis include not only production constraints but also economic, institutional, and climatic imbalances in the global food system. An analysis of global food production has shown that leading producing countries (China, India, the United States, and Brazil), as well as Kazakhstan, have increased grain production over the past ten years. However, this increase in production has not been accompanied by a comparable reduction in hunger, confirming the dominant role of economic access to food and the sustainability of agricultural production over a simple increase in physical output.

Kazakhstan, and in particular the Kostanay region, plays a key role in ensuring regional food security due to its grain specialization and export-oriented agricultural production. However, the study revealed that the region's agriculture operates in a high-risk farming zone and is highly sensitive to climatic factors, primarily precipitation levels and interannual climate variability. Stochastic modeling results confirmed a statistically significant relationship between climatic parameters and grain yields. It has been established that water availability is a key factor in the sustainability of agricultural production, while increasing climate instability increases economic risks, reduces the predictability of business results, and negatively impacts production profitability.

Taken together, the obtained results allow us to conclude that sustainable economic development of agriculture in the face of climate change is impossible without integrating climate factors into regional economic planning and agricultural policy. For the Kostanay region, measures aimed at reducing climate risks, increasing the resilience of grain production, and adapting the agricultural sector to long-term changes in environmental conditions are a priority. The practical relevance of the study lies in the potential use of the findings in developing regional programs for sustainable agricultural development, establishing government support mechanisms, and substantiating investment and technological decisions aimed at strengthening food security and the economic sustainability of agricultural production in the Kostanay region.

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Information about the authors:

Naurzbayev Bolatbek Temirbekovich – Candidate of Economic Sciences, PhD, Agricultural scientist, Head of a peasant farm, Republic of Kazakhstan, Kostanay, email: naurzbaev.bolatbek@icloud.com.*

Ayulov Abilmazhin Mussaipovich – Doctor of Economic Sciences, Professor, Rector of the Humanitarian-Technical Academy, Republic of Kazakhstan, 020000, Kokshetau, 1 Zhambyl Zhabayev Str., e-mail: rector@gta.kz; https://orcid.org/0009-0002-6590-4855.

Naurzbayeva Kamila Bolatbekovna – Head of the New projects launch team, Allur plant, SaryarkaAvto Prom LLP, Republic of Kazakhstan, Kostanay, 41 Promyshlennaya Str., e-mail: kamila08saveme80d@gmail.com.

Наурзбаев Болатбек Темирбекұлы – Экономика ғылымдарының кандидаты, агроном, шаруа қожалығының басшысы, Қазақстан Республикасы, Қостанай; электрондық пошта: naurzbaev.bolatbek@icloud.com.*

Аюлов Әбілмәжін Мұсаипұлы – экономика ғылымдарының докторы, профессор; ректор; Гуманитарлық-техникалық академия; Қазақстан Республикасы 020000 Жамбыла Жабаева көш., 1, Көкшетау қ.; электрондық пошта: rector@gta.kz ; https://orcid.org/0009-0002-6590-4855.

Наурзбаева Камила Болатбекқызы – «СарыаркаАвтоПром» ЖШС «Аллюр» зауытының жаңа жобаларды іске қосу тобының жетекшісі, Қазақстан Республикасы, Қостанай қ., Промышленная, 41; электрондық пошта: kamila08saveme80d@gmail.com.

Наурзбаев Болатбек Темирбекович – кандидат экономических наук, PhD, учёный агроном, глава крестьянского хозяйства, Республика Казахстан, 110000 г. Костанай, e-mail: naurzbaev.bolatbek@icloud.com.*

Аюлов Абильмажин Мусаипович – доктор экономических наук, профессор, ректор, Гуманитарно-техническая академия, Республика Казахстан, 020000 г. Кокшетау, ул. Жамбыла Жабаева, 1, e-mail: rector@gta.kz, https://orcid.org/0009-0002-6590-4855.

Наурзбаева Камила Болатбековна – руководитель группы запуска новых проектов, завод «Аллюр», ТОО «СарыаркаАвтоПром», Республика Казахстан, 110000 г. Костанай, Промышленная, 41, e-mail: kamila08saveme80d@gmail.com.