



The Spread of Moisture Deficit: Preconditions for Intensified Aridification in Kazakhstan and Russia

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ABSTRACT

This study examined the impact of climate change on grain crop yields in Kazakhstan and Russia between 1991 and 2023, highlighting the urgent need for adaptive agricultural strategies. The research focused on changes in weather patterns—specifically decreased precipitation and rising temperatures—in Northern and Central Kazakhstan, as well as in Russia's Tula Region. Regression analysis was employed to address the relationship between these climatic factors and agricultural yields. The findings reveal a notable decline in precipitation during the growing season, with levels dropping from 158mm to 137mm in Northern Kazakhstan and from 267mm to 257mm in the Tula Region. Average annual temperatures have increased by 0.9°C in Kazakhstan and 1.3°C in Russia, intensifying the risk of droughts. The analysis demonstrates a strong correlation between crop yields and both precipitation and air temperature, underscoring the adverse effects of aridification on agriculture. In light of these findings, the study emphasizes the necessity for adaptation strategies, such as the adoption of drought-resistant crop varieties and the implementation of optimized water management practices. These measures are essential for strengthening agricultural resilience to climate change and ensuring sustainable development in the region. The insights gained from this research can inform effective government policies and agricultural programs to achieve long-term agricultural sustainability in Kazakhstan and Russia amid changing climatic conditions.

Keywords: Air temperature, Precipitation levels, Agricultural adaptation, Climate change, Ecosystem resilience.

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INTRODUCTION

The global water crisis is among the most pressing challenges for sustainable development, driven by interconnected factors such as climate change, population growth, intensified agriculture, urbanization, ecosystem degradation, and inefficient water management (Ventsova & Safonov, 2021; Wanjari et al., 2024). Global warming alters climate zones, reduces snow cover, accelerates glacier melting, and increases the frequency of extreme

weather events, such as droughts and floods, which disrupt the hydrological cycle and affect both the availability and quality of water resources (Mohammadi et al., 2023).

Agriculture, which accounts for over 70% of global freshwater withdrawals, is particularly vulnerable. Intensive irrigation, unsustainable land use, and contamination by agrochemicals contribute to soil salinization, groundwater depletion, and biodiversity loss (Cheng et al., 2022; Ge et al., 2023). Water scarcity, especially in arid and semi-arid regions, leads to desertification, land degradation, reduced

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soil moisture, and declining yields of key crops such as wheat, while also threatening drinking water quality and public health (Kirilenko & Sedjo, 2007; Abdrakhimov et al., 2024).

In Northern Kazakhstan, water deficits result from the combined effects of climatic changes and anthropogenic pressures, including overgrazing, removal of windbreaks, and inefficient irrigation practices using outdated open canals, with losses exceeding 40% before reaching fields (Filimonov et al., 2016; Tusupbekov & Ryapolova, 2019; Vinogradova et al., 2021). Similar trends are observed in Central Kazakhstan and parts of European Russia, where declining grain yields threaten regional food security and cross-border supply chains (Drizhd et al., 2020; Vorobyova & Smagulov, 2021).

Addressing these challenges requires integrated adaptation strategies in agriculture. Key approaches include the development and cultivation of drought-resistant crop varieties; optimization of irrigation technologies, such as drip irrigation; precision soil moisture monitoring; and the use of modern digital tools, including GIS, satellite monitoring, and climate scenario modeling (Babkenov et al., 2020). Regional specificity must be considered, as soil, climate, and socioeconomic conditions differ across steppe regions of Northern and Central Kazakhstan and adjacent areas of European Russia. Implementing these measures can help mitigate the environmental, economic, and social risks associated with water scarcity, ensuring sustainable agricultural production, food security, and resilience in the face of climate variability.

The global water crisis and climate change pose significant challenges to sustainable development, affecting both water availability and agricultural productivity (Ventsova & Safonov, 2021; Wanjari et al., 2024). Moisture deficits, driven by altered precipitation patterns, increased evaporation, and extreme weather events, have particularly severe impacts in arid and semi-arid regions, such as Northern and Central Kazakhstan, as well as parts of European Russia (Vorobyova & Smagulov, 2021; Abdrakhimov et al., 2024). These changes disrupt the hydrological cycle, reduce soil moisture, and compromise irrigation efficiency, leading to declining yields of key crops, desertification, and threats to food security (Cheng et al., 2022; Ge et al., 2023).

The impact of climate change on the environment is therefore one of the most pressing concerns. Moisture deficit, as a complex natural phenomenon, directly affects plant physiology and growth. Changes in weather patterns have increased the frequency and intensity of extreme events, such as droughts, floods, and temperature anomalies (Harris et al., 2020; Yurova et al., 2021; Zhong, 2024). Insufficient soil moisture alters the water regime of plants, reducing photosynthetic efficiency and slowing growth. Under severe moisture deficiency, root systems fail to absorb sufficient water, which may ultimately result in plant stress or mortality. These effects are especially detrimental for moisture-sensitive crops, including corn, sunflower, and wheat (Harris et al., 2020; Kashyap & Agarwal, 2021).

The impact of climate change on agriculture and ecosystems is one of the most pressing concerns in Northern and Central Kazakhstan, as well as in European Russia. Climate variability has led to moisture deficits, increased frequency and intensity of droughts, floods, and temperature anomalies, and altered precipitation patterns, thereby intensifying aridification and affecting soil moisture, plant growth, and crop yields (Ding et al., 2021; Jiao et al., 2021; Yurova et al., 2021). Insufficient soil moisture reduces photosynthesis, slows plant growth, and can cause mortality in moisture-sensitive crops such as corn, sunflower, and wheat (Siddig et al., 2020; Kashyap & Agarwal, 2021; Zhong, 2024). Rising temperatures and low humidity further exacerbate water deficits, particularly in steppe and semi-arid regions, leading to more severe droughts and negative impacts on agriculture, livestock, and ecosystems (Usupayev et al., 2020; Ray & Goel, 2021; Tusupbekov et al., 2022).

In Northern Kazakhstan, climate change is a major driver of declining soil moisture, reducing water availability for agriculture and natural vegetation and contributing to lower yields of key crops such as wheat (Kenenbaev, 2020; Espolov et al., 2023; Pashkov et al., 2024). Similar patterns are observed in Central Kazakhstan, particularly in Karaganda Region, where rising temperatures, declining precipitation, and soil degradation negatively affect grain yields, highlighting the urgent need for adaptive agricultural strategies (Shcherba, 2010; Vorobyova & Smagulov, 2021).

In European Russia, regions such as Tula are experiencing comparable challenges. Long-term studies indicate a temperature rise of approximately 1.5°C and a 10–20% reduction in precipitation, leading to increased drought frequency and reduced grain yields (Cherenkova & Zolotokrylin, 2016; Zolotokrylin et al., 2020). Similar trends have been documented in Central and Northwestern Russia, where temperature increases of 2–2.5°C and significant precipitation declines have contributed to lower agricultural productivity.

While climatic shifts are the primary driver of moisture deficits, anthropogenic factors such as overgrazing and unsustainable land management practices also play an important role in intensifying aridification and affecting crop yields (Tokbergenova et al., 2018; Dmitriyev et al., 2023; Toishimanov et al., 2024). Overall, the literature emphasizes that moisture deficits, driven by both climate and human activities, are a major threat to agricultural stability. Developing and implementing adaptive strategies, including drought-resistant crops, improved irrigation, and soil management, is therefore crucial to maintain grain production and ensure food security in these vulnerable regions.

This study investigated the impact of alterations in climate conditions on grain yields in Northern and Central Kazakhstan, as well as in European Russia. The aim was to analyze how these regions respond to climate shifts and to identify effective methods for adapting agricultural practices. The research tasks included analyzing temperature and precipitation dynamics in Kazakhstan and European Russia, assessing their effects on grain yields, and

developing adaptive strategies to mitigate the damage caused by climate change to agriculture in both regions.

MATERIALS & METHODS

Research Stages

The research was conducted in several stages:

1. Data Collection and Processing: Meteorological data from selected regions were collected and processed using a variety of statistical tools. Descriptive statistics (mean values, standard deviations) were used to assess changes in temperature and precipitation. Trend analysis was conducted using linear regression and time-series methods, including 5-year moving averages, to identify long-term climate trends (IPCC, 2021; FAO, 2025). The strength of the relationships between climatic variables and crop yields was evaluated using determination coefficients (R^2), multiple correlation coefficients (R), and analysis of variance (ANOVA) (Montgomery, 2017).
2. Analysis of Results: The study assessed the impact of climate change on water resources, agricultural climate conditions, and agricultural production in Northern and Central Kazakhstan and European Russia.
3. Formulation of Adaptation Strategies: The study

developed strategies for adapting the agricultural sector and proposed recommendations for improving agricultural practices in Northern and Central Kazakhstan and European Russia.

Data

To analyze the impact of changes in weather patterns on grain yields in Northern and Central Kazakhstan, the study examined meteorological data from five weather stations located in grain-producing areas of these regions. In Northern Kazakhstan, data were collected from stations in Ruzaevka (Northern Kazakhstan), Kostanay (Kostanay Region), Esil (Akmola Region), and Irtyshsk (Pavlodar Region). Central Kazakhstan was represented by data from Karaganda (Karaganda Region). For European Russia, data from Tula (Tula Region) were analyzed (Fig. 1).

The analysis of meteorological data included average air temperatures and precipitation during the growing season (May–August) for the period 1961–2023. In addition, extreme air temperatures, daily temperature variations, and precipitation were assessed both annually and for specific periods of 2023, including the warm period (June–October), the cold period (November–March), and the spring period (April–May).

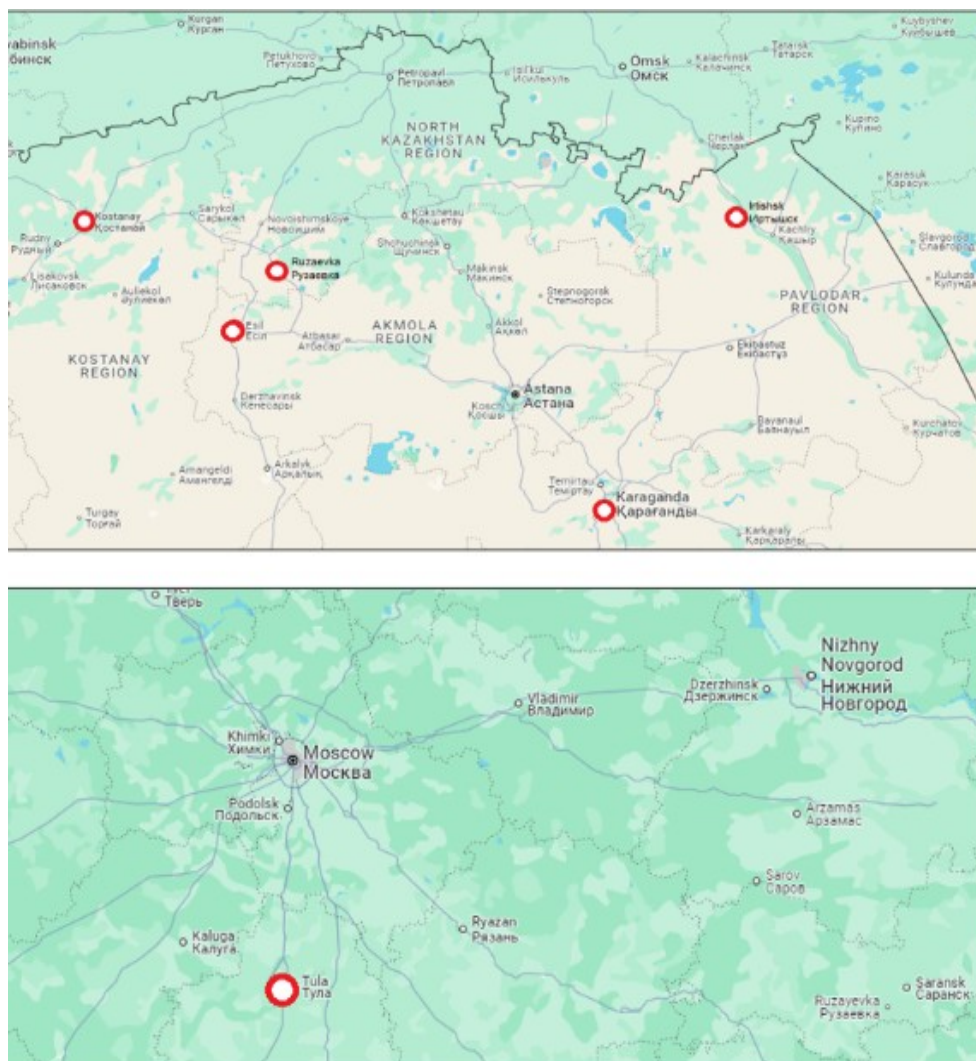


Fig. 1: Map of the study areas: Kazakhstan and European Russia; Note: Red circles indicate the meteorological stations included in the analysis.

Methods of Analysis

The study employed correlation-regression analysis, time series analysis, trend assessment based on 63 years of meteorological station data, variability analysis, and water balance analysis. These methods were used to assess the influence of climate on agricultural productivity and identify long-term trends and cyclical changes. Additionally, they enabled an assessment of weather patterns and their impact on agriculture in Northern/Central Kazakhstan and European Russia.

The study utilized the hydrological-climatic calculation (HCC) system of equations (Kusainova et al., 2021). HCC is regarded as the most comprehensive and versatile mathematical model for moisture transformation processes in catchment areas across any territory. This approach rests on the fundamental conservation laws of energy and matter and represents a unique genetic methodology that differs from conventional evaporation calculation techniques. HCC has been applied for both static and dynamic moisture descriptions over continuous time intervals under various physical-geographical conditions across many regions of Russia and adjacent territories. The method has demonstrated strong convergence with field data. To validate the results, the study compared the calculated soil moisture and runoff values with the measured data.

Due to the absence or extreme sparsity of the actinometric station network in many areas, it is necessary to use empirical formulas to determine the thermal energy resources of total evaporation based on aggregated meteorological station data:

$$T_z = 17.6 \Sigma t + 400 \quad (1)$$

where Σt denotes the sum of positive average monthly air temperatures for the year;

T_z represents the thermal energy resources for evaporation in MJ/(m²·year).

The annual sum of the water equivalent for the value T_z can be determined using Formula 2:

$$Z_m = T_z / L = 7\Sigma t + 160 \quad (2)$$

where Σt is the sum of positive average monthly air temperatures for the year;

Z_m denotes the maximum possible evaporation in mm/year. $L = 2.512 \text{ MJ}/(\text{m}^2 \cdot \text{cdotop})$ is the latent heat of evaporation.

The structure of the relationships between heat resources and moisture resources determines the level of moisture β_{KX} :

Formula 3 represents the moisture index for the region during any intra-annual period of an average year:

$$\beta_{\text{KX}} = \frac{KX}{Z_m} \quad (3)$$

where KX is the amount of atmospheric precipitation (in mm), adjusted by a correction factor to compensate for underestimation by measurement instruments.

The moisture-deficiency indicator for the region (ΔKX) is calculated as the difference between atmospheric precipitation (KX) and the water-equivalent of thermal energy resources (Z_m).

$$\Delta KX = KX - Z_m \quad (4)$$

Periodization

The study covered two periods: the baseline period (1961-1990), which served as the reference, and the contemporary period (1991-2023), which was analyzed for comparison. The study examined changes in climate parameters and cereal crop yields to identify long-term trends and variations. This periodization aligns with global climate research standards (IPCC, 2021; NASA GISS, 2023).

Analysis of Results

Data processing and statistical analysis were performed using R for regression analysis, trend visualization, and the construction of correlation matrices, while Microsoft Excel was employed for primary data entry and basic statistical operations.

Software

Statistical analysis was conducted using software programs such as R and Excel.

Limitations

The study relied on data collected from a limited number of meteorological stations and within a restricted timeframe. Therefore, the findings may insufficiently capture the full spectrum of climatic variations and their associated impacts.

RESULTS

In Northern Kazakhstan, significant shifts in climatic conditions have occurred over recent decades, marked by rising air temperatures and seasonal variations in atmospheric precipitation. These changes have contributed to moisture deficits in certain areas of the region. In the forest-steppe zone, the average annual air temperature rises by 0.3-0.33°C per decade, while the steppe zone experiences an increase of 0.2-0.43°C during the same timeframe.

In Central Kazakhstan, Karaganda Region has also seen warming trends, with average annual temperatures rising by +0.2°C over the last 10 years and by +0.7°C over the last 30 years. Annual precipitation increased by approximately 45mm during the same period. These trends reflect a broader pattern of warming and increased moisture across the region.

Russia's Tula Region saw a 0.4°C rise in average annual temperatures over the past decade, alongside a 30mm increase in annual precipitation. These developments suggest a general trend toward warmer and wetter conditions, potentially linked to ongoing climate change. Overall, in Northern and Central Kazakhstan and the Tula Region, weather pattern changes are characterized by rising air temperatures and variations in atmospheric precipitation patterns. These changes can contribute to localized and seasonal moisture deficits (Table 1).

The climate of Karaganda Region in Kazakhstan is sharply continental and extremely arid. The duration of sunshine, a primary climatic factor, ranges from 2,300 to 2,500 hours per year, peaking in July. Annual total solar radiation reaches approximately 110-120kcal/cm². The region experiences the influence of three main types of air masses: Arctic, temperate, and tropical.

Table 1: Dynamics of average annual air temperature and atmospheric precipitation in Kazakhstan and Russia

Zone	Meteorological Station	Average Annual Air	Average Annual Air	Temperature Change (°C) over 10 Years	Average Annual	Average Annual	Precipitation Change (mm)
		Temperature (°C) 1961-1990	Temperature (°C) 1991-2023		Precipitation (mm) 1961-1990	Precipitation (mm) 1991-2023	
Forest-Steppe Zone	Ruzaevka	2.1	2.9	+0.3	336	363	+27mm
Forest-Steppe Zone	Kostanay	2.8	3.8	+0.3	325	353	+28mm
Steppe Zone	Esil	2.7	3.4	+0.2	252	284	+32mm
Steppe Zone	Irtysk	2.0	3.0	+0.3	288	288	0mm
Steppe Zone	Karaganda	3.3	4.0	+0.2	333	378	+45mm
Forest-Steppe Zone	Tula	4.7	6.0	+0.4	586	626	+40mm

In January, average temperatures range from -18°C in the north to -14°C in the south, with absolute minima reaching -52°C and -44°C , respectively. The average temperature in July (the warmest month) varies from $+18^{\circ}\text{C}$ in the north to $+22^{\circ}\text{C}$ in the south, with maximum temperatures reaching $40-43^{\circ}\text{C}$. Winters are marked by frequent snowstorms. The number of snowstorm days ranges from 21 to 38, occasionally exceeding 50 days in some areas. Thunderstorms in the region are often accompanied by squalls, heavy rainfall, and hail. A distinct feature of the region's climate is its pronounced aridity. Severe droughts occur approximately once every 10-12 years. Winters in Karaganda Region can be severe, lasting between 5 and 5.5 months. Stable snow cover typically forms by mid-November and persists for 110-150 days. The number of frost days with temperatures falling below -25°C varies across the region, ranging from 10-15 to 40-50 days per year. In some years, this can increase to 20-25 days in a single month.

The region is divided into four climatic zones based on moisture and thermal conditions: (1) moderately cool, arid, small-hill areas (Karaganda and mountainous parts of Aktogay); (2) moderately warm, arid, small-hill areas (Bukhar-Zhyrau, Abai, Nurin, northeastern Osakarov, and northeastern Karaganda); (3) moderately warm, very arid areas (Osakarov, northern Zhanaarka, and southeastern Karaganda); and (4) warm, very arid areas (western, southwestern, and southern regions—semi-desert and desert plains) (Filimonov et al., 2016).

At the Irtysk meteorological station, the growing season (May-August) saw a temperature increase from 17.6°C in 1961-1970 to 18.5°C in 2011-2023, with a particularly notable rise occurring in the last thirty years. Concurrently, the amount of precipitation during the growing season at the Irtysk station decreased from 158mm in 1961-1970 to 137mm in 2011-2023. When combined with rising temperatures, this reduction in available water resources fosters aridification. The moisture coefficient for the growing season (May-August)—the ratio of precipitation to evaporation—decreased from 0.38 to 0.21, further confirming a deterioration in moisture conditions (Table 2).

An analysis of linear trends in precipitation in Northern Kazakhstan from 1961 to 2023 revealed a decline in precipitation during the growing season at the Irtysk meteorological station. In contrast, other stations analyzed in the study saw a slight increase in precipitation. However, over the past 30 years, there has been a reduction in total precipitation during the growing season. This reduction, along with other hydro-meteorological factors, has contributed to moisture deficits and subsequent aridification. Linear trends towards decreased precipitation

over the past decade were identified at the meteorological stations in Ruzaevka, Kostanay, Irtysk, Esil, and Karaganda. The coefficients of determination (R^2) range from 0.01 to 0.28, indicating that these trends moderately explain the variation in precipitation data.

In Karaganda, Central Kazakhstan, the mean annual precipitation is 378mm, which corresponds to the normal precipitation level for the region. The linear trend in precipitation over the past decade shows a decreasing tendency, with an average annual reduction of 10mm/year. The coefficient of determination (R^2) is 0.22, demonstrating a moderate correlation between precipitation patterns and time. Overall, both regions of Kazakhstan are experiencing climatic changes characterized by rising air temperatures and variations in atmospheric precipitation. These processes lead to moisture deficits in certain areas and during specific periods of the year.

The mean annual precipitation in the Tula Region is 626mm. The linear trend for precipitation shows an increase of 30mm per year from 2011 to 2023. The coefficient of determination (R^2) for the region is 0.47, suggesting a relatively strong relationship between time and precipitation. Approximately 47% of the variation in precipitation can be explained by the linear trend (Table 3).

The study found that annual precipitation in Northern and Central Kazakhstan has been gradually decreasing over time, falling from 380-400mm in 2011 to 280-370mm in 2023. This downward trend indicates a reduction in available water resources, which may adversely affect agricultural production and overall environmental sustainability. European Russia, particularly the Tula Region, has experienced an increase in precipitation over the last decade. Additionally, a notable decrease in average monthly precipitation during July—the wettest month of the year—was observed at the Kostanay station. Specifically, precipitation levels dropped from 65mm in 1961-1970 to 47mm in 2001-2010.

According to data from the Esil meteorological station (1961-2023), the growing season precipitation declined from 147mm in 1961-1970 to 125mm in 1981-1990, compared to the seasonal norm of 150mm. This reduction in precipitation intensifies the problem of water scarcity, particularly as evaporation rates increase.

Evaporation (Z_m) at the Esil meteorological station has shown an upward trend, increasing from 603mm in 1961-1970 to 640mm in 2001-2010. This reflects a rise in moisture loss from soil and vegetation, largely driven by higher air temperatures. As a result, the region's water balance has deteriorated, as indicated by a declining water balance coefficient (β_{kh}), which represents the ratio of precipitation to evaporation. In Esil, this coefficient fell from 0.24 in 1961-1970 to 0.20 in 1981-1990, pointing to

Table 2: Time series analysis of climatic factors for the growing season (May-August) at the Irtysk meteorological station

Period (years)	Average Air Temperature for the Growing Season (May-August) (°C)	Average Precipitation for the Growing Season (May-August) (mm)	Humidity Coefficient for the Growing Season (May-August)
1961-1970	17.6	158	0.38
1971-1980	17.2	166	0.30
1981-1990	18.1	131	0.23
1991-2000	18.1	159	0.30
2001-2010	18.2	169	0.29
2011-2023	18.5	137	0.21

Table 3: Assessment of Linear Trends in Precipitation (2011-2023)

Weather Station in Northern Kazakhstan	Average Annual Precipitation (mm)	Linear Trend in Precipitation (mm/year)	Coefficient of Determination (R ²)
Ruzaevka	363	-10 to -11	0.28
Kostanay	353	-2 to -3	0.01
Esil	288	-2 to -3	0.06
Irtysk	284	-2 to -3	0.01
Karaganda	378	-10 to -11	0.22
Tula	626	+30 to +31	0.47

Table 4: Water Balance Calculations Using the Hydroclimatic Method (HCM) for the Growing Season (May-August) at the Esil Meteorological Station from 1961 to 2023

Period (years)	ΔKX – Deficit of Moisture (mm)	KH – Precipitation (mm)	Z _m – Maximum Possible Evaporation (mm)	β_{KX} Water Balance Coefficient
1961-1970	-456	147	603	0.24
1971-1980	-474	140	614	0.23
1981-1990	-497	125	622	0.20
1991-2000	-485	147	632	0.23
2001-2010	-496	144	640	0.23
2010-2023	-474	163	637	0.26

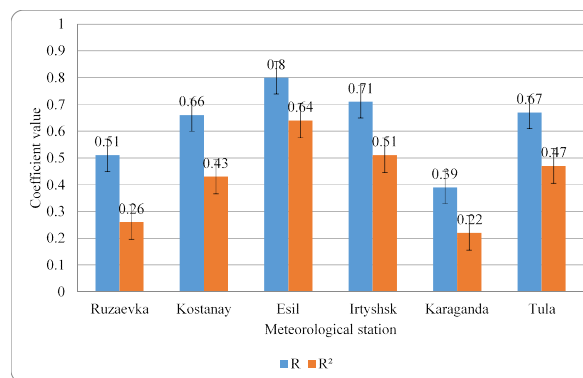
an exacerbation of arid conditions. Between 2010 and 2023, the decline in the water balance continued: the moisture deficit increased to 474mm, evaporation reached 637mm, and the water balance coefficient dropped to 0.26. These changes confirm the ongoing intensification of aridity in the region (Table 4).

An analysis of the water balance in Northern and Central Kazakhstan over the study period revealed ongoing water regime degradation, characterized by declining atmospheric precipitation and rising evaporation rates. The observed moisture decrease poses significant risks to agricultural production and regional ecological sustainability. In Karaganda Region, the average annual precipitation is 380mm. This value is roughly comparable to that of the more humid areas in Northern Kazakhstan, largely due to local topographical features. The linear trend for precipitation in Karaganda indicates a decrease of 10mm per year, with a moderate correlation between precipitation and time ($R^2 = 0.22$).

In Russia's Tula Region, a moderate positive correlation was observed between average annual precipitation and the linear precipitation trend ($R = 0.67$, $R^2 = 0.47$). The relatively high standard errors of R (0.63) and R^2 (0.63) indicate considerable uncertainty in the estimated relationship. The study examined the impact of climatic factors on crop yields, using data on average monthly air temperature and precipitation during the growing season—key indicators of thermal potential and water availability (Fig. 2).

Data from the Esil meteorological station in the Akmolinsk region revealed the strongest correlations between meteorological factors and crop yields. The model assessment indicated that the coefficient of determination (R^2) is 0.64, suggesting that nearly 64% of the variability in crop yields can be explained by the model, which incorporates the effects of air temperature and precipitation during the growing season. Furthermore,

a high multiple correlation ($R = 0.80$) indicates a statistically significant relationship between crop yields and the two key variables included in the model: average monthly air temperature and total precipitation during the plant growth period.

**Fig. 2:** Regression analysis of crop yield formation in relation to meteorological factors; Note: R – multiple correlation coefficient; R^2 – coefficient of determination (variance).

Crop yields largely depend on two primary climatic factors: atmospheric precipitation and air temperature during the growing season (May-August for cereal crops). During this period, precipitation deficits and elevated temperatures can lead to drought conditions. Consequently, crop yield levels serve as an indicator of climatic aridity in the region.

Recommendations for Adapting Agricultural Practices to Changing Climatic Conditions

Adapting agricultural practices to changing climatic conditions requires a combination of strategies aimed at enhancing resilience, optimizing resources, and improving productivity. Key measures include selecting

drought- and heat-resistant crops and varieties, adopting crop rotation and intercropping systems, and introducing species better suited to evolving temperature and precipitation patterns. Efficient water management is critical, encompassing modern irrigation technologies, rainwater collection and storage, and programs to maintain and restore water resources.

Soil management should focus on preserving moisture, enhancing fertility, and preventing erosion to maintain productivity under climate stress. Modern agricultural equipment and automation can further improve water and soil management, increasing the adaptability of operations to variable conditions. Monitoring and forecasting systems are essential for timely decision-making, while predictive models can support planning and risk management.

Education, training, and knowledge transfer ensure that farmers and agronomists are equipped with the skills and information needed to implement adaptive practices effectively. Finally, supportive policies and investment in research create the conditions for sustainable adoption of climate-resilient strategies.

Overall, implementing these integrated measures will strengthen the resilience of the agricultural sector, mitigate risks associated with climate variability, and contribute to sustainable and stable production.

The implementation of these recommendations is expected to facilitate the adaptation of the agricultural sector to variable climate conditions, mitigate risks, and maintain productivity and stability in agriculture. The proposed measures will ensure sustainable agricultural production and strengthen the competitiveness of agricultural producers in the context of climate change.

DISCUSSION

Analysis of climatic parameters in Northern and Central Kazakhstan and European Russia demonstrates significant warming trends and changes in precipitation, with profound implications for agriculture. Over the past decades, average annual temperatures in these regions have increased by 0.9–2°C, exceeding global averages in some areas (Semenova, 2021; Bissenbayeva et al., 2025). At the same time, precipitation has generally declined by 20–22 mm, particularly during critical growth periods, resulting in increasing aridification, moisture deficits, and reduced soil moisture. These climatic shifts create conditions conducive to heat stress and drought, which negatively affect the yields of key cereal crops such as wheat, barley, and corn (Cao et al., 2023; Birimbayeva et al., 2024; Guzueva et al., 2024).

Statistical analyses reveal strong correlations between climate variables and crop yields. At the Esil meteorological station, the R^2 of 0.64 highlights the substantial influence of temperature and precipitation changes on cereal production, confirming that climatic variability is a major driver of yield fluctuations (Zhichkin et al., 2020; Semenova, 2021). Similar patterns are observed in Central Kazakhstan, particularly in Karaganda Region, where rising temperatures, declining precipitation, and soil degradation reduce grain yields and threaten regional food security

(Cherenkova & Zolotokrylin, 2016; Akulov et al., 2024). In European Russia, the Tula Region has experienced a temperature rise of 1.2°C over the past century and reductions in precipitation, leading to more frequent and severe droughts and floods, which adversely impact agricultural productivity (Zolotokrylin et al., 2020; Grigorieva & Livenets, 2022).

These findings are consistent with broader research showing that rising temperatures exacerbate drought propagation and intensify evapotranspiration stress, affecting water availability for crops and ecosystems (Sardans et al., 2024; Liu et al., 2025a, 2025b; Yan et al., 2025). Climate modeling studies predict further shifts in the hydrological regime of Kazakh rivers, with potential seasonal flow changes that could worsen water stress in the future (Kusainova et al., 2020, 2021, 2024; Nurbatsina et al., 2025; Tursunova et al., 2025). Bissenbayeva et al. (2025) additionally document the spatiotemporal intensification of aridity in Central Kazakhstan, which, combined with anthropogenic pressures, increases vulnerability of agricultural systems.

Overall, the evidence indicates that climate change is a primary driver of aridification, moisture deficits, and declining crop yields in Northern and Central Kazakhstan and European Russia (Kenetayeva & Kryazheva, 2018; Kenetayeva et al., 2021, 2022). While regional variations exist, both areas face significant agricultural risks that require adaptive strategies. Effective responses include the cultivation of drought- and heat-resistant crop varieties, optimization of irrigation technologies, improved soil management, and integration of climate forecasting tools (Safonov et al., 2018; Petrova et al., 2024). Coordinated efforts among government agencies, scientific institutions, and agricultural producers are essential to mitigate climate risks, maintain food security, and ensure sustainable development in the region.

Conclusions

This comparative analysis of weather pattern changes in Russia and Kazakhstan highlights the substantial impact of climate change on agriculture and the economy. In Northern Kazakhstan, the average annual air temperature has risen by 0.2–0.43°C over the past decade, while precipitation has decreased, contributing to water scarcity and increased aridification. Time series data from 1961 to 2023 indicate a temperature increase of 0.9°C and a reduction in precipitation from 158mm to 137mm during the growing season (May–August). These changes reflect a progressive decline in regional water availability and an increased risk of drought.

Similarly, in Central Kazakhstan, the average annual air temperature has increased by 0.2°C over the last decade. Seasonal fluctuations in temperature and precipitation may result in water shortages in specific locations and time frames. In Karaganda, the average annual precipitation reaches 380mm—approximately equivalent to that in the relatively wetter areas of Northern Kazakhstan—due to the region's topographical features. The linear trend in precipitation in Karaganda shows a consistent decrease of 10mm per year.

In the Tula Region, the growing season precipitation (May-August) has also declined (from 267mm to 257mm), while the average annual air temperature has risen by 1.3°C. These changes suggest an increasing probability of drought conditions. Regression analysis revealed a pronounced relationship between crop yields and climatic variables (precipitation and air temperature) during the growing season. The strongest correlation was observed in the Akmolinsk region of Kazakhstan, emphasizing the critical role of climate in determining agricultural productivity.

To adapt agriculture to changing climatic conditions, it is recommended to implement drought-resistant crop varieties, optimize water management systems, improve soil processing methods, and modernize agricultural equipment. Effective agricultural management in arid climates requires climate monitoring and forecasting systems. Furthermore, it would be beneficial to provide training for farmers in the use of modern agricultural technologies. Additionally, government support plays a crucial role in mitigating the adverse effects of climate change on water resources and agriculture.

The findings of this study hold practical relevance for enhancing the resilience and productivity of agriculture in arid climates. Future research should prioritize the development and refinement of climate models to improve the accuracy of temperature and precipitation forecasts and to better assess their implications for water resources and agriculture. Thus, a comprehensive approach to addressing the challenges posed by climate change in agriculture should encompass the development of effective monitoring and forecasting systems, farmer education, and government support. This strategy would minimize the negative impacts of climate change and enhance the resilience and productivity of the agricultural sector.

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REFERENCES

- Abdrakhimov, R.G., Akzharkynova, A.N., Rodrigo-Illari, J., Nahiduzzaman, K.M., Dautaliyeva, M.E., & Rodrigo-Clavero, M.E. (2024). Assessment of changes in hydrometeorological indicators and intra-annual river runoff in the Ile River basin. *Water*, 16(13), 1921. <https://doi.org/10.3390/w16131921>
- Akulov, N., Rubtsova, M., Akulova, V., Ryzhov, Y., & Smirnov, M. (2024). Aeolian sands of the temperate boreal zone (Northern Asia). *Quaternary*, 7(4), 55. <https://doi.org/10.3390/quat7040055>
- Babkenov, A.T., Babkenova, S.A., Abdullayev, K.K., & Kairzhanov, Y.K. (2020). Breeding spring soft wheat for productivity, grain quality, and resistance to adverse external factors in Northern Kazakhstan. *Journal of Ecological Engineering*, 21(6), 8-12. <https://doi.org/10.12911/22998993/123160>
- Birimbayeva, L., Makhmudova, L., Alimkulov, S., Tursunova, A., Mussina, A., Tigkas, D., Beksultanova, Z., Rodrigo-Claver, M.-E., & Rodrigo-Illari, J. (2024). Analysis of the spatiotemporal variability of hydrological drought regimes in the lowland rivers of Kazakhstan. *Water*, 16(16), 2316. <https://doi.org/10.3390/w16162316>
- Bissenbayeva, S., Shokparova, D., Abuduwailli, J., Samat, A., Ma, L., & Ge, Y. (2025). Spatiotemporal dynamics of the Aridity Index in Central Kazakhstan. *Sustainability*, 17, 7089. <https://doi.org/10.3390/su17157089>
- Cao, L., Xu, C., Suo, N., Song, L., & Lei, X. (2023). Future dry-wet climatic characteristics and drought trends over arid Central Asia. *Frontiers in Earth Science*, 11, 1102633. <https://doi.org/10.3389/feart.2023.1102633>
- Cheng, M., Zhang, M., Van Veldhuizen, R.M., & Knight, C.W. (2022). Temperature and precipitation changes impact the yields of small grain cultivars from 1978 to 2018 in Fairbanks and Delta Junction, Alaska. *Arctic, Antarctic, and Alpine Research*, 54(1), 386-394. <https://doi.org/10.1080/15230430.2022.2109785>
- Cherenkova, E.A., & Zolotokrylin, A.N. (2016). On the comparability of some quantitative drought indicators. *Fundamental and Applied Climatology*, 2, 79-94.
- Ding, Z., Ali, E.F., Elmahdy, A.M., Ragab, K.E., Seleiman, M.F., & Kheir, A.M. (2021). Modeling the combined impacts of deficit irrigation, rising temperature and compost application on wheat yield and water productivity. *Agricultural Water Management*, 244, 106626.
- Dmitriyev, P., Fomin, I., Ismagulova, S., Berdenov, Z., Zuban, I., Ostrovnoy, K., & Golodova, I. (2023). Study of the possibility of using the bottom organomineral accumulations of the Lakes of the North Kazakhstan Region to obtain innovative fertilizers for the development of organic farming and agrotourism. *Sustainability*, 15(11), 8999. <https://doi.org/10.3390/su15118999>

- Drizhd, N.A., Khaydina, M.P., Usupayev, S.E., Rabatuly, M., Alexandrov, A., & Kenetayeva, A.A. (2020). Reserves and extraction of coalbed methane in the Karaganda basin. *Current Scientific Research in the Modern World*, 2-1(58), 80-88.
- Espolov, T., Espolov, A., Satanbekov, N., Tireuov, K., Mukash, J., & Suleimenov, Z. (2023). Economic trend in developing sustainable agriculture and organic farming. *International Journal of Sustainable Development & Planning*, 18(6), 1885. <https://doi.org/10.3390/su1715708910.18280/ijsdp.180624>
- FAO (2025). Water efficiency, productivity and sustainability in the NENA regions (WEPS-NENA). <https://www.fao.org/in-action/water-efficiency-nena/activities/nexus-framework/es/>
- Filimonov, E.N., Portnov, V.V., Yegorov, V.V., Steflyuk, Y.Y., & Kenetayeva, A.A. (2016). Some aspects of the study of the gas content of seam K10 under the conditions of the Abay Mine, UD AO AMT. Karaganda.
- Ge, Y., Wu, N., Abuduwalli, J., & Issanova, G. (2023). Assessment of spatiotemporal features and potential sources of atmospheric aerosols over the Tianshan Mountains in arid central Asia. *Atmospheric Environment*, 294, 119502. <https://doi.org/10.3390/su1715708910.1016/j.atmosenv.2022.119502>
- Grigorjeva, E., & Livenets, A. (2022). Risks to the health of Russian population from floods and droughts in 2010–2020: A scoping review. *Climate*, 10(3), 37. <https://doi.org/10.3390/su1715708910.3390/cli10030037>
- Guzeva, E., Kulpeis, Y., & Smagulova, K. (2024). Socio-economic impacts and energy efficiency of smart housing in smart city initiatives. *BIO Web of Conferences*, 140, 02008. <https://doi.org/10.3390/su1715708910.1051/bioconf/202414002008>
- Harris, I., Osborn, T.J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, 7, 109. <https://doi.org/10.3390/su1715708910.1038/s41597-020-0453-3>
- IPCC (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/>
- Jiao, Y., Liu, J., Li, C., Qiu, Q., Zhang, X., & Yu, F. (2021). Evolution of meteorological factors during 1980–2015 in the Daqing River Basin, North China. *Journal of Water and Climate Change*, 12(7), 2977-2992. <https://doi.org/10.3390/su1715708910.2166/wcc.2021.205>
- Kashyap, D., & Agarwal, T. (2021). Temporal trends of climatic variables and water footprint of rice and wheat production in Punjab, India from 1986 to 2017. *Journal of Water and Climate Change*, 12(4), 1203-1219. <https://doi.org/10.3390/su1715708910.2166/wcc.2020.093>
- Kenenbaev, S.B. (2020). The role of biological means in organic agriculture. *Siberian Herald of Agricultural Science*, 50(3), 103-110. <https://doi.org/10.26898/0370-8799-2020-3-11>
- Kenetayeva, A.A., & Kryazheva, T.V. (2018). Fundamentals of georisk assessment in the city of Karaganda and Karaganda Region, Kazakhstan. *Republican Scientific-Theoretical Journal "Engineering Bulletins of Universities of Kyrgyzstan"*, 11, 31-36.
- Kenetayeva, A.A., Usupayev, S.E., Kryazheva, T.V., Rabatuly, M., Salkeyeva, A.K., & Sembayeva, G.N. (2021). Demethanization of coal seams in the Karaganda basin. IOP Conference Series: Earth and Environmental Science, 677(4), 042118. <https://doi.org/10.1088/1755-1315/677/4/042118>
- Kenetayeva, A.A., Usupayev, S.E., Shaikhova, G.S., Salkeyeva, A.K., Akhmetova, A.Z., & Mullagalijeva, L.F. (2022). Natural conditions of the Karaganda region. IOP Conference Series: Earth and Environmental Science, 981(3), 032041. <https://doi.org/10.1088/1755-1315/981/3/032041>
- Kirilenko, A.P., & Sedjo, R.A. (2007). Climate change impacts on forestry. *Proceedings of the National Academy of Sciences of the United States of America*, 104(50), 19697-19702. <https://doi.org/10.1073/pnas.0701424104>
- Kusainova, A.A., Mezentseva, O.V., & Tusupbekov, Z.A. (2020). Influence of precipitation variability and temperature conditions on the yield of grain crops in Northern Kazakhstan. IOP Conference Series: Earth and Environmental Science, 548(4), 042026. <https://doi.org/10.1088/1755-1315/548/4/042026>
- Kusainova, A.A., Mezentseva, O.V., Tusupbekov, Z.A., & Volkovskaya, N.P. (2021). Spatial distribution of moisture deficit on the territory of the south of Western Siberia and Northern Kazakhstan. IOP Conference Series: Earth and Environmental Science, 677(4), 042078. <https://doi.org/10.1088/1755-1315/677/4/042078>
- Kusainova, A., Mezentseva, O., & Tusupbekov, Z. (2024). Investigation of the conditions for the formation of moisture deficiency in Northern Kazakhstan using the method of hydrological and climatic calculations. *E3S Web of Conferences*, 524, 03015. <https://doi.org/10.1051/e3sconf/202452403015>
- Liu, J., Zhao, J., He, J., Qu, J., Xing, Y., Du, R., Chen, S., Tang, X., Wang, L., & Yue, C. (2025a). Spatiotemporal trend and influencing factors of surface soil moisture in Eurasian drylands over the past four decades. *Forests*, 16(4), 589. <https://doi.org/10.3390/f16040589>
- Liu, Y., Wang, Y., Zhao, Y., Chen, S., Wang, L., Yang, W., Li, X., Li, X., Lei, H., Chang, H., Zhai, J., Zhu, Y., Wang, Q., & Ye, T. (2025b). Increasing sensitivity to soil moisture deficits predominantly intensifies evapotranspiration stress in a greening China. *EGUsphere*, Preprint. <https://doi.org/10.5194/egusphere-2024-3764>
- Mohammadi, S., Rydgren, K., Bakkestuen, V., & Gillespie, M.A. (2023). Impacts of recent climate change on crop yield can depend on local conditions in climatically diverse regions of Norway. *Scientific Reports*, 13(1), 3633. <https://doi.org/10.1038/s41598-023-30813-7>
- Montgomery, D.R. (2017). *Growing a revolution: Bringing our soil back to life*. W. W. Norton & Company.
- NASA GISS (2023). Global Temperature Time Series. NASA GISS Surface Temperature Analysis (GISTEMP v4). <https://data.giss.nasa.gov/gistemp/>
- Nurbatsina, A., Tursunova, A., Makhmudova, L., Salavatova, Z., & Huthoff, F. (2025). Projected hydrological regime shifts in Kazakh Rivers under CMIP6 climate scenarios: Integrated modeling and seasonal flow analysis. *Atmosphere*, 16, 1020. <https://doi.org/10.3390/atmos16091020>
- Pashkov, S.V., Imashev, E.Z., Baubekova, G.K., Kaimuldinova, K.D., Tokpanov, Y.A., Nurgaliyeva, G.Z., Baimukasheva, G.K., Kenzhebay, R.N., Kassenov, S.K., & Ukrainskiy, P.A. (2024). Ecological-economic and ethno-cultural determinants of the development of organic farming in Kazakhstan. *Sustainability*, 16(10), 4065. <https://doi.org/10.3390/su16104065>
- Petrova, I.Y., Miralles, D.G., Briant, F., Donat, M.G., Min, S.-K., Kim, Y.-H., & Bador, M. (2024). Observation-constrained projections reveal longer-than-expected dry spells. *Nature*, 633, 594-600. <https://doi.org/10.1038/s41586-024-07887-y>
- Ray, L.K., & Goel, N.K. (2021). Spatio-temporal change in rainfall over five different climatic regions of India. *Journal of Water and Climate Change*, 12(7), 3124-3142. <https://doi.org/10.2166/wcc.2021.052>
- Safonov, V.A., Mikhalev, V.I., & Chernitskiy, A.E. (2018). Antioxidant status and functional condition of respiratory system of newborn calves with intrauterine growth retardation. *Agricultural Biology*, 53(4), 831-841. <https://doi.org/10.15389/agrobiology.2018.4.831eng>
- Sardans, J., Miralles, A., Tariq, A., Zeng, F., Wang, R., & Peñuelas, J. (2024). Growing aridity poses threats to global land surface. *Communications Earth & Environment*, 5, 776. <https://doi.org/10.1038/s43247-024-01935-1>
- Semenova, I. (2021). Spatiotemporal distribution of soil moisture content over Ukraine and its relationship to atmospheric conditions. *Environmental Sciences Proceedings*, 4(1), 20. <https://doi.org/10.3390/ecas2020-08117>
- Shcherba, T.E. (2010). Intensification of aridization of territory due to anthropogenic factors in Russia during the summer. *Bulletin of Moscow State University. Series Soil Science*, 2, 22-31.
- Siddig, K., Stepanyan, D., Wiebelt, M., Grethe, H., & Zhu, T. (2020). Climate change and agriculture in the Sudan: Impact pathways beyond changes in mean rainfall and temperature. *Ecological Economics*, 169, 106566. <https://doi.org/10.1016/j.ecolecon.2019.106566>
- Toishimanov, M., Suleimenova, Z., Myrzabayeva, N., Dossimova, Z., Shokan, A., Kenenbayev, S., Yessenbayeva, G., & Serikbayeva, A. (2024). Effects of organic fertilizers on the quality, yield, and fatty acids of maize and soybean in Southeast Kazakhstan. *Sustainability*, 16(1), 162. <https://doi.org/10.3390/su16010162>
- Tokbergenova, A., Kiyassova, L., & Kairova, S. (2018). Sustainable development agriculture in the Republic of Kazakhstan. *Polish Journal of Environmental Studies*, 27(5), 1923-1933. <https://doi.org/10.15244/pjoes/78617>
- Tursunova, A., Saparova, A., Kulebayev, K., Baspakova, G., Nurbatsina, A., Myrzakhetmetov, A., Bazarbek, A., & Huthoff, F. (2025). Assessment of future water stress on surface waters in the West Kazakhstan region caused by the combined impacts of climate change and increased anthropogenic pressure. *Sustainability*, 17, 10699. <https://doi.org/10.3390/su172310699>
- Tusupbekov, Z.A., & Ryapolova, N.L. (2019). Soil moisture regimes and moisture deficiencies territories of Northern Kazakhstan. In *Materials of the All-Russian (national) conference. Actual problems of environmental management, water use, agrochemistry. Soil science and ecology* (pp. 67–73). Omsk.
- Tusupbekov, Z.A., Mezentseva, O.V., & Kusainova, A.A. (2022). Assessment

- of long-term variability of heat-water balance characteristics during the growing season of the territory of Northern Kazakhstan. *IOP Conference Series: Earth and Environmental Science*, 1010, 012067. <https://doi.org/10.1088/1755-1315/1010/1/012067>
- Usupayev, S.E., Kenetayeva, A.A., Tenchurina, A.R., Shaikhova, G.S., & Zhenbayev, A.M. (2020). The history of the development of the Karaganda basin. *Current Scientific Research in the Modern World*, 5-4(61), 28-35.
- Ventsova, I., & Safonov, V. (2021). The role of oxidative stress during pregnancy on obstetric pathology development in high-yielding dairy cows. *American Journal of Animal and Veterinary Sciences*, 16(1), 7-14. <https://doi.org/10.3844/ajavsp.2021.7.14>
- Vinogradova, V., Titkova, T., & Zolotokrylin, A. (2021). How climate change is affecting the transitional natural zones of the Northern and Arctic regions of Russia. *Polar Science*, 29, 100652. <https://doi.org/10.1016/j.polar.2021.100652>
- Vorobyova, T., & Smagulov, Y. (2021). Mapping dynamics of agricultural land use in the dry steppe zone of the Northern Kazakhstan. *InterCarto*, 27, 5-18. <https://doi.org/10.35595/2414-9179-2021-4-27-5-18>
- Wanjari, R.N., Shah, T.H., Telvekar, P., Bhat, F.A., Abubakr, A., Bhat, B.A., Darve, S.I., Ramteke, K.K., Mathialagan, D., Magloo, A.H., & Singh, B.S. (2024). Assessing ecosystem health: A preliminary investigation of the gosikhurd dam ecosystem structure and functioning, an appraisal based on ecological modelling, India. *Environmental Monitoring and Assessment*, 196(9), 815. <https://doi.org/10.1007/s10661-024-12958-8>
- Yan, H., Sun, N., Yao, L., Thurber, T.B., & Rice, J.S. (2025). Rising temperatures intensify drought propagation and severity across the contiguous United States. *npj Natural Hazards*, 2, 91. <https://doi.org/10.1038/s44304-025-00134-y>
- Yurova, A.Y., Bure, V.M., & Lukyanova, R.Y. (2021). Global climate and soil cover of Russia: Manifestations of drought, prevention, control measures, elimination of the consequences and adaptation measures (agriculture and forestry) (Vol. 3). LLC "IBA Publishing House". <https://doi.org/10.52479/978-5-6045103-9-1>
- Zhichkin, K.A., Starikov, P.V., Zhichkina, L.N., Mamaev, O.A., Artemova, E.I., & Levochkina, N.A. (2020). The applied software role in the training of economic specialties students. *Journal of Physics: Conference Series*, 1691(1), 012111. <https://doi.org/10.1088/1742-6596/1691/1/012111>
- Zhong, H. (2024). Unintended distortion of regulating water use: Evidence from China. *Journal of Regional Science*, 64(5), 1680-1711. <https://doi.org/10.1111/jors.12721>
- Zolotokrylin, A.N., Titkova, T.B., & Cherenkova, E.A. (2020). Characteristics of spring–summer drought in dry and wet periods in the south of European Russia. *Arid Ecosystems*, 10, 322-328. <https://doi.org/10.1134/S2079096120040216>