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Agro-Climatic Zoning of the Territory of Northern Kazakhstan for Zoning of Agricultural Crops Under Conditions of Climate Change

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Abstract: Assessments of the agro-climatic resources of Northern Kazakhstan are urgently needed in the face of climate change and increasing threats to food security in the world, and they can provide valuable information for specialists in the field of agriculture. To assess the agro-climatic conditions of Northern Kazakhstan, the following agro-climatic indices were used: heat availability, moisture availability, and aridity of the growing season for the period 1991–2023. The research results rendered it possible to build maps of the spatial distribution of agro-climatic indicators, and five agro-climatic zones, ranging from "moderately humid moderately warm" in the north to "very arid moderately hot" in the south of Northern Kazakhstan, were identified. Recommendations were developed with respect to the agro-climatic zoning of main crops, taking into account the climatic resources of Northern Kazakhstan. The data obtained will be used for the strategic planning of the agricultural crop industry in Northern Kazakhstan.

Keywords: agro-climatic zoning; vegetation period; heat availability; moisture availability; aridity; agricultural crops

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1. Introduction

Climatic resources, as one of the main natural resources, determine the potential for agricultural development. Knowledge of climatic resources and their distribution over the territory allows for the optimal placement of agricultural facilities and crops. Knowledge of positive climate features and the patterns of adverse weather events allows for maximizing benefits and minimizing damage.

In Kazakhstan, the area of arable land is 26.4 million ha, of which 19.3 million ha is located in the northern regions of Kazakhstan (Kostanay region—6.3 million ha; Akmola region—6.1 million ha; Severo-Kazakhstan region—4.9 million ha; Pavlodar region—2.0 million ha) [1].

In recent decades, changes in climatic conditions have been observed globally, which have resulted in long-term changes to weather conditions. These changes have an impact on plant growth, photosynthesis rate, transpiration, and moisture availability, as well as the quantity, quality, and productivity of crops. In the future, these conditions will seriously affect the production of agricultural products in the world and their accessibility to the population [2].

Central Asia is one of the driest regions in the world, and this makes it very sensitive to climatic changes in the region with respect to global warming and fluctuations in precipitation, which will increase the intensity of evaporation and the frequency and risk of drought [3–6]. Research studies show that in the future the intensity and risk of drought will increase and cause a serious shortage of water resources in Central Asia [7,8]. According to climate scenarios, in 2071–2100, the temperature in the surface layer will increase by an average of 3–7 °C compared to the second half of the 20th century [9,10]. In Northern Kazakhstan, there is an increase in heat availability of the growing season, with an increase in the sum of active air temperatures by 50–75 °C/10 years. Simultaneously, the duration of the growing season increases by 2–4 days/10 years. Moreover, in the summer seasons, there is a drying tendency [11].

Since 1976, the global rate of increase in the average annual air temperature has been 0.18 °C/10 years, and in Kazakhstan, it increases by 0.32 °C/10 years. Since the mid-1970s, positive anomalies of the average annual and average seasonal temperature of the surface air layer have been observed in Kazakhstan [12].

The authors of [13] present the results of an assessment of modern space–time trends with respect to extreme air temperature and precipitation values at 42 meteorological stations throughout Kazakhstan from 1971 to 2020. Temperature indices confirmed the warming trend. Trends in the precipitation index were statistically insignificant in most of the country.

In another study [14], using the modeling of the PRECIS regional model (Providing Regional Climate for Impact Studies), bioclimatic changes in Kazakhstan up to the middle of the 21st century were estimated. It is forecasted that the seasonality of the climate will increase by 36.2% relative to the territory, in addition to an increase in continentality by 7.3% and an increase in summer aridity by 9.7%. Climate change results in bioclimatic homogenization with a loss of 27% of bioclimatic diversity.

In the context of climate change, the importance of studying agro-climatic conditions is increasing, even in regions with favorable climatic conditions. For example, in Europe, 12 to 67% of the changes in wheat yield from year to year are a result of the influence of agro-climatic factors [15].

Our previous studies have shown that by 2050, the moisture availability of the growing season is expected to reduce by 10–16%, and an increase in climate aridity by 10–15% may occur, which may result in a decrease in the yield of spring wheat by 30–40% [16].

To cultivate suitable crops, regional climatic conditions are taken into account as they directly affect their development, biological productivity, and ultimately the profitability of the crop production industry and the economy of the region [17].

Agro-climatic indices are used to zone agro-climatic conditions for the purpose of cultivating crops, taking into account parameters such as moisture availability, heat availability, aridity of the region, etc. [18].

Agro-climatic zoning takes into account meteorological conditions in combination with plant requirements to determine appropriate, suitable, or unsuitable conditions for crop cultivation [19].

The results of agro-climatic zoning can be reflected on maps, using GIS technologies to indicate their spatial location in the region [20,21].

The authors of [22] report the need to update agro-climatic norms relative to climate warming. Their research has shown a shift in the boundaries of agro-climatic zones in Russia and Kazakhstan.

In another study [23], the modern climatic norms of the main indicators of the heat supply of the growing season in the Almaty region, located in the south of Kazakhstan, were established.

The authors of [24] carried out an investigation on the zoning of the Almaty region according to indicators of heat and moisture availability; five agro-climatic zones were identified.

In the agro-climatic guides of the northern regions of Kazakhstan prepared by us in 2017, meteorological data averaged over the 1981–2016 period were used [25–28]. Today, the Republican State Enterprise "Kazhydromet" of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan uses data averaged over the 1991–2020 period as a climatic norm. Therefore, a decision was made to update the assessment of the agro-climatic resources of Northern Kazakhstan based on updated meteorological data. In addition, adjustments were carried out on the maps of the agro-climatic zoning of the territory.

Due to climate change, it has become necessary to re-evaluate agro-climatic resources and the zoning of crops in the territory of Northern Kazakhstan.

The analysis showed that the regions of Northern Kazakhstan differ in heat and moisture availability. We hypothesized that the agro-climatic zoning of the territory of Northern Kazakhstan with respect to heat and moisture supply will increase the sustainability of grain production and mitigate the negative impact of climate change.

The purpose of this study is to examine the agro-climatic zoning of the territory of Northern Kazakhstan for the zoning of agricultural crops, and this is investigated based on an assessment of heat and moisture availability.

The main objectives of the study are as follows: (i) analysis of the heat and moisture availability of the growing season in Northern Kazakhstan; (ii) agro-climatic zoning of the territory of Northern Kazakhstan; and (iii) development of recommendations for the zoning of major agricultural crops in Northern Kazakhstan.

We have updated the values of agro-climatic indicators based on modern data for the 1991–2023 period instead of the previously used data for the 1981–2016 period. We have also improved the previously constructed agro-climatic maps on the heat availability, moisture availability, and aridity of the growing season based on modern climatic data. We propose a division of the entire territory of the Republic of Kazakhstan into eight agro-climatic zones. Simultaneously, each zone is divided into 2–3 subzones depending on the availability of heat. The previously developed map of the agro-climatic zoning of the territory of Northern Kazakhstan was improved on the basis of modern climatic data. The humidification coefficient K was used instead of the hydrothermal coefficient of G.T. Selyaninov (HTC). Based on the heat and moisture availability of the growing season, the zoning of agricultural crops in the agro-climatic zones of Northern Kazakhstan was carried out.

2. Data and Methods

2.1. Study Area

The territory of Northern Kazakhstan includes the Kostanay, Akmola, Severo-Kazakhstan, and Pavlodar regions, and the area of agricultural land is 15,617,000 hectares [29]. Northern Kazakhstan stretches from the south to the north from 48° to 55° north latitude, and it stretches from the west to the east from 60° to 79° east longitude (Figure 1A).

Climatic conditions are continental, and this is caused by large differences in air temperatures during seasons characterized by cold and long winters and hot summers due to the geographical location in the center of Eurasia [29].

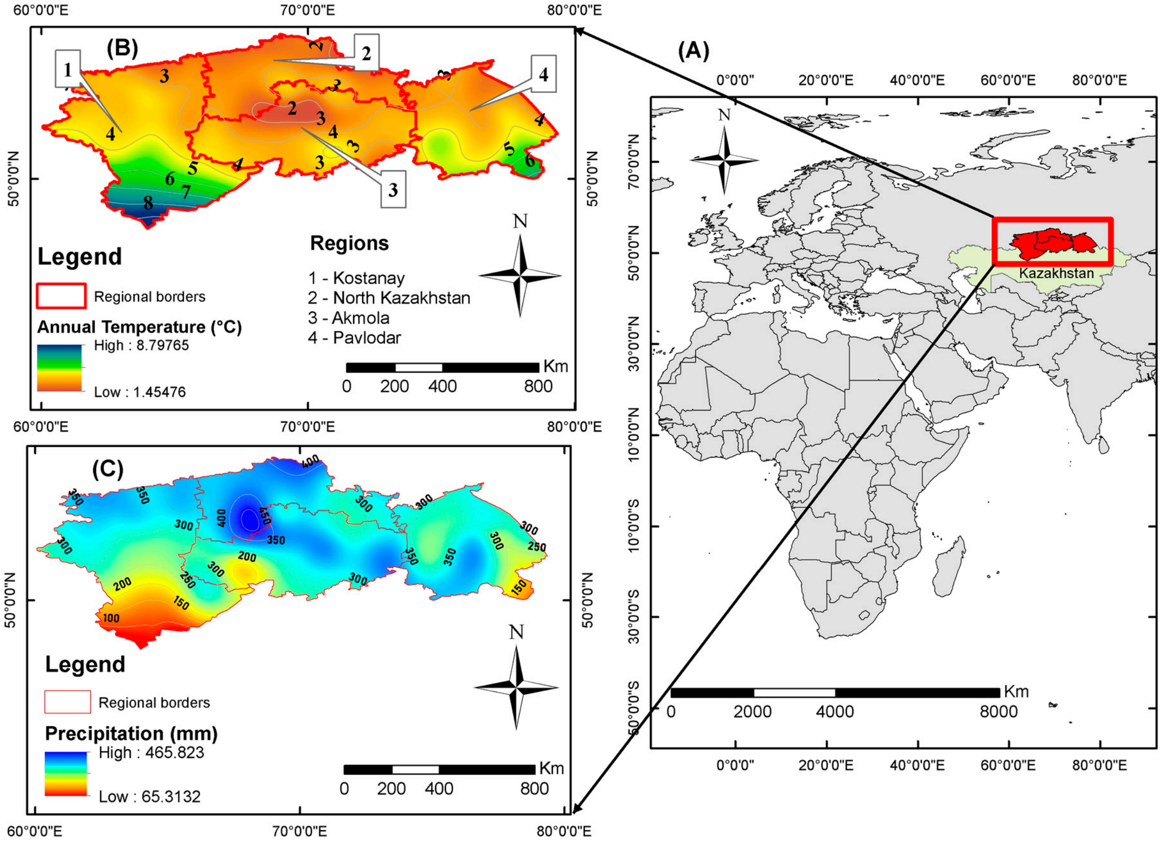

Figure 1. Map of study area in Northern Kazakhstan: (**A**) location and geographical information; (**B**) spatial allocation of annual temperature (°C); (**C**) spatial allocation of annual precipitation (mm).

The spatial distribution of the annual air temperature ranges from 1.4 °C to 8.8 °C. (Figure 1B). The precipitation falls within a range of 350–450 mm (Figure 1C), and in the southern areas, less than 100 mm of precipitation is observed due to the remoteness of seas and oceans.

In general, the flat part of the region is marked by a continuous gentle slope towards the north and northeast with weak dissection, and the average height is 125–200 m above sea level (Figure 1B).

Lowlands are generally found in large lake depressions in the southeastern part of the study area. The elevation of relief is observed to be within 250–400 mainly in the western part of the Kostanay region; from 300 to 600 m in the Akmola region; reaching 800–900 m in some locations; and from 200 to 800–900 m in the southwestern part of the Pavlodar region [30].

Northern Kazakhstan is mainly represented by steppe and forest-steppe zonal landscapes, which are characterized by hollows, uplands, and flat and hilly plains with the presence of grasses and steppe meadows, birch and aspen groves and forests on chernozems (leached, ordinary, and meadow), and gray forest saline soil [31].

2.2. Data

In this study, data from 62 meteorological stations (MS) (Figure 2) of the Republican State Enterprise "Kazhydromet" of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan were used for the period from 1991 to 2023. Daily, decadal (10 days), and monthly air temperature and precipitation data were used. Long-term data were processed via climatological and statistical data processing methods.

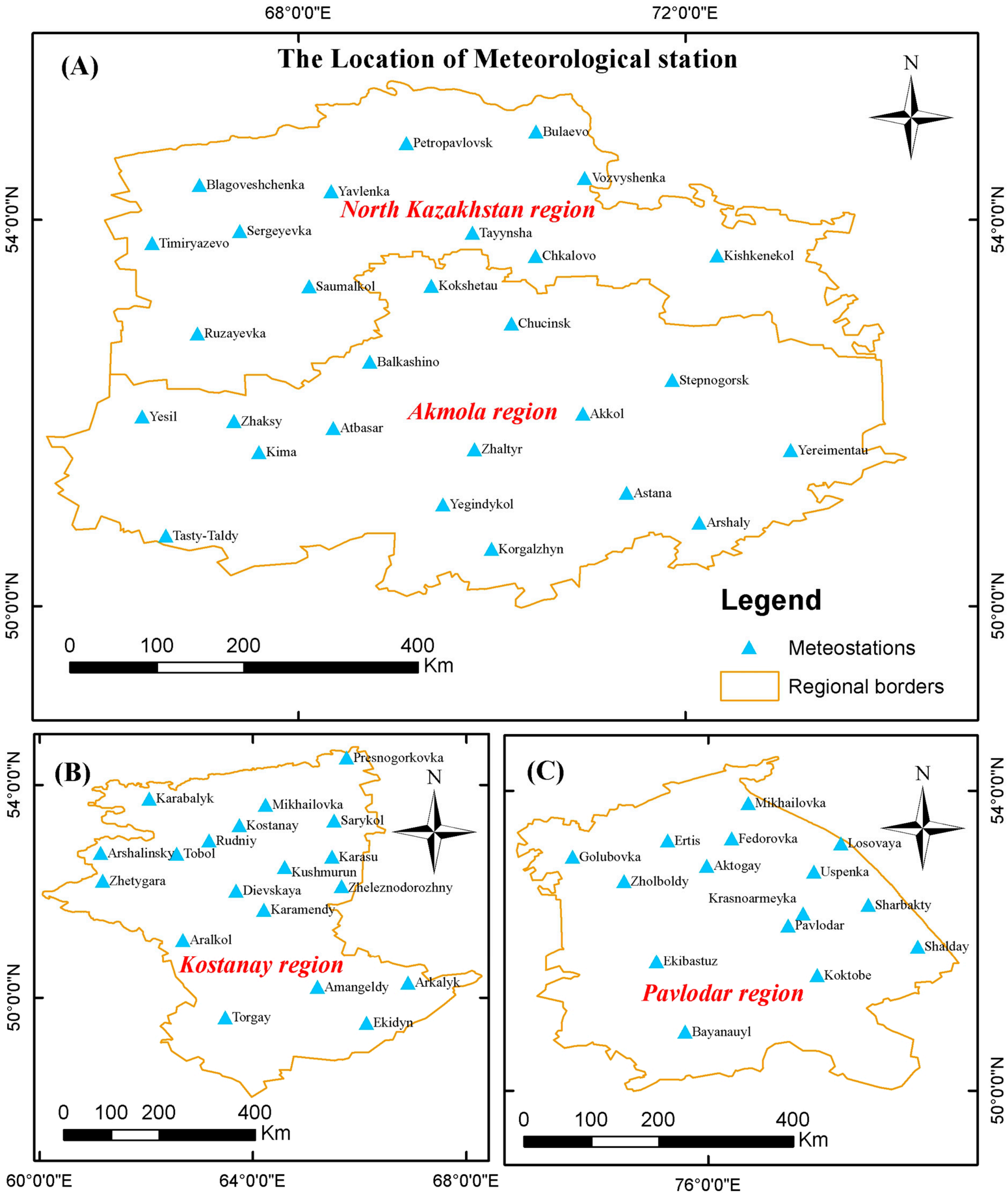

Figure 2. Location of meteorological stations in Northern Kazakhstan: (**A**) Severo-Kazakhstan and Akmola region; (**B**) Kostanay region; and (**C**) Pavlodar region.

2.3. Methods

2.3.1. Assessment of Heat Availability During Vegetation Period

Plant growth and development start from the stable transition date with an average daily air temperature above the level of the plants' biological minimum temperature. The biological minimum air temperature for early spring crops is 5 °C; for late spring crops, it is 10 °C; and for heat-loving crops, it is 15 °C. For example, the biological minimum temperature required for the development of vegetative organs is 5 °C for wheat, 12 °C for millet, and 15 °C for cotton and rice [32–35].

To characterize the heat availability of the growing season, the following are used: the dates of the transition of air temperature through 5 °C, 10 °C, and 15 °C in spring and autumn; the duration of periods with such temperatures; and the sum of the average daily air temperatures for these periods. In the temperate zone, the duration of the period with average daily air temperatures above 10 °C corresponds to the growing season of most agricultural crops [33,35]. Therefore, the thermal resource values of the growing season are often estimated using the sum of active air temperatures above 10 °C (the sum of the average daily air temperatures for the period with temperatures above 10 °C).

2.3.2. Assessment of Moisture Availability and Dryness of Growing Season

Various indices are widely used to assess moisture availability and dryness of the growing season: moisture coefficients, hydrothermal coefficient of G. Selyaninov (HTC), Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Water Supply Index (SWSI), etc. [33,36,37].

When determining drought in Southern Russia (south of 55° N) via HTC, SPI, SPEI, and PDSI indices, HTC and SPI were more accurate, and PDSI was less accurate. To determine the intensity of drought according to the HTC data, it is proposed to use gradations for each weather station [38].

Studies have shown that with respect to Kazakhstan's conditions, SPI determines drought with a greater error than HTC [39].

In Northern Kazakhstan, with respect to the correlation coefficient between wheat yields and HTC, K is 0.63–0.79 [40].

In the present study, moisture availability of the growing season was assessed via the wetting coefficient K, which was proposed by S. Baisholanov, and the dryness of the growing season was assessed via the hydrothermal coefficient of G. Selyaninov (HTC). These methods are the most suitable for the conditions of Kazakhstan [25,40,41].

$$K = \frac{0.5 \sum R_{11-4} + \sum R_{5-8}}{0.12 \sum T_{5-8}} \quad (1)$$

$$HTC = \frac{\sum R_{5-8}}{0.1 \sum T_{5-8}} \quad (2)$$

where $\sum R_{11-4}$ is the sum of precipitation for November–April; $\sum R_{5-8}$ is the sum of precipitation for May–August; and $\sum T_{5-8}$ is the sum of daily air temperatures above 10 °C for May–August.

The evaluation criteria gradations via K and HTC (Tables 1 and 2) were adapted for the agro-climatic conditions of Northern Kazakhstan, i.e., they were refined in accordance with the long-term fluctuations of spring wheat yields [40].

Table 1. Criteria for assessment of moisture availability via K.

K Range	Degree of Moisture Availability
≥1.40	Excess moisture
1.00–1.39	Optimal and sustainable moisture availability
0.80–0.99	Sufficient but not sustainable moisture availability
0.60–0.79	Insufficient moisture availability
0.40–0.59	Moderate moisture deficit
0.20–0.39	Severe moisture deficit
<0.20	Dry

Table 2. Criteria for assessing aridity via HTC.

HTC Range	Degree of Aridity
≥0.80	Non-arid
0.60–0.79	Slightly arid
0.40–0.59	Moderately arid
0.20–0.39	Severely arid
<0.20	Dry

Accordingly, the agro-climatic indicators of the heat and moisture availability of the vegetation period were used.

- Duration of the period with average daily air temperatures above 10 °C, which characterizes the duration of the vegetation period.
- Sum of the average daily air temperatures above 10 °C, which characterizes the heat availability of the vegetation period.
- Moisture coefficient K, which characterizes moisture availability during the growing season.
- Hydrothermal coefficient (HTC)—drought index—which characterizes the dryness of the growing season.

2.3.3. The Agro-Climatic Zoning of the Territory

For a comprehensive assessment of the agro-climatic resources of the territory, zoning is carried out based on agro-climatic indicators. Agro-climatic zoning provides for the division of the territory into zones that are sufficiently homogeneous within their borders according to certain characteristics.

Agro-climatic zoning facilitates the development of solutions for a number of practical and scientific problems in agriculture. Using agro-climatic zones, it is possible to plan agricultural practices better (sowing, harvesting, tillage, etc.) and to zone crops according to agro-climatic conditions.

In Kazakhstan, the agro-climatic zoning of the territory is carried out according to the moisture coefficient K and the sum of the active air temperatures above 10 °C (ΣT_{10}). The criteria K and ΣT_{10} presented in Tables 3 and 4 are used [25].

Table 3. Criteria for assessing territory's humidification.

K	Humidification
≥1.40	Excessively humid
1.20–1.39	Abundantly moist
1.00–1.19	Moderately humid
0.80–0.99	Slightly moist
0.60–0.79	Slightly arid
0.40–0.59	Moderately arid
0.20–0.39	Very arid
<0.20	Dry

Table 4. The criteria for assessment of the heat availability of the territory.

ΣT_{10}, °C	Heat Availability
2000–2500	Moderately warm
2500–3000	Warm
3000–3500	Moderately hot
3500–4000	Hot
>4000	Very hot

In agro-climatic reference books, the flat territory of the northern part of Kazakhstan contains six agro-climatic zones [25–28].

In 2021, within the framework of the UNDP/GEF project "Development of zoning schemes and landscape planning for sustainable management of key biodiversity areas in the Almaty region" [42,43], S. Baisholanov conducted the agro-climatic zoning of plain and mountainous agricultural territories located in the southeast of Kazakhstan.

Within the framework of this study, taking into account the agro-climatic zoning of the plain and mountainous agricultural territories of Kazakhstan, a decision was made to divide the entire territory of the republic into eight agro-climatic zones. Each zone was subdivided into 2–3 subzones based on heat availability (Table 5).

Table 5. The agro-climatic zones of the territory of the Republic of Kazakhstan.

№	Name of the Zone	K	ΣT_{10}, °C
I	(a) Excessively humid moderately warm (b) Excessively humid warm	≥1.40	2000–2500 2500–3000
II	(a) Abundantly humid moderately warm (b) Abundantly humid warm (c) Abundantly humid moderately hot	1.2–1.4	2000–2500 2500–3000 3000–3500
III	(a) Moderately humid moderately warm (b) Moderately humid warm (c) Moderately humid moderately hot	1.0–1.2	2000–2500 2500–3000 3000–3500
IV	(a) Slightly humid moderately warm (b) Slightly humid warm (c) Slightly humid moderately hot	0.8–1.0	2000–2500 2500–3000 3000–3500
V	(a) Slightly arid warm (b) Slightly arid moderately hot (c) Slightly arid hot	0.6–0.8	2500–3000 3000–3500 3500–4000
VI	(a) Moderately arid warm (b) Moderately arid moderately hot (c) Moderately arid hot	0.4–0.6	2500–3000 3000–3500 3500–4000
VII	(a) Very arid moderately hot (b) Very arid hot	0.2–0.4	3000–3500 3500–4000
VIII	(a) Dry hot (b) Dry very hot	<0.2	3500–4000 >4000

2.3.4. Determining the Feasibility of Crop Cultivation

Based on the analysis of heat and moisture availability of the growing season, as well as soil fertility, the expediency of growing crops in a given area is determined. To carry this out, the compliance of climatic resources with the requirements of agricultural crops is assessed. Simultaneously, 80–90% of the provision of agricultural crops with climatic resources is sufficient [32].

The first determining factor is heat availability. To determine the provision of plants with heat, it is necessary to compare the biological sum of temperatures required for plants ($\sum T_b$) with the climatic sum of the temperatures (ΣT_{10}). For moderately heat-loving crops, the sum of the daily air temperatures above 10 °C is taken; for heat-loving crops, the sum above 15 °C is taken [32–35].

Several scientific studies [25,32–35,44] have provided the heat demand of agricultural crops (cereals, legumes, oilseeds, and technical and vegetable crops), expressed as a biological sum of the air temperatures for 55° N. Due to the photoperiodic response when moving southwards from 55° N, the biological sum of the temperatures for long-day plants increases; for short-day plants, it decreases; and for neutral plants, it does not change. Corrections are carried out from minus 10 °C to 25 °C for every 1° of latitude.

Northern Kazakhstan is situated within 48–55° N; therefore, the biological sums of the temperatures are given at 52° N. To facilitate the analysis, crops were grouped via heat demand ($\sum T_b$), with a gradation step of 200 °C. For moderately heat-loving crops (A1–A9), the biological sum of the air temperatures above 10 °C was given; for heat-loving crops (B1–B5), it was given above 15 °C (Table 6) [25].

Table 6. Distribution of crops into groups based on heat demand.

Group	$\sum T_b$, °C	Crop (e—Early Maturing; m—Medium Maturing; ml—Medium–Late; l—Late Maturing)
A1	1200–1400	Buckwheat—e; buckwheat—m; barley—e; oats—e; peas—e; potatoes—e; cucumbers—e; cucumbers—m.
A2	1400–1600	Buckwheat—e; barley—m; barley—l; oats—m; peas—m; peas—l; potatoes—m; cucumbers—l; wheat—e; beans—e; pravin—e; lentils—e; lentils—m; chickpea—e; chickpea—m; lupin—e; oilseed–flax—e; oilseed–flax—m; long-lasting flax—e; long-lasting flax—m; cabbage—e; cabbage—m; tomatoes—e.
A3	1600–1800	Potatoes—l; barley—l; oats—l; wheat—m; millet—e; millets—m; beans—m; pravin—m; chickpeas—l; lupins—m; cabbages—l; tomatoes—m; tomatoes—l.
A4	1800–2000	Wheat—l; millet—l; beans—l; sunflower—e; canola—e.
A5	2000–2200	Lupin—l; sunflower—m; canola—l; sugar beet—e.
A6	2200–2400	Sunflower—l; soybean—e; sugar beet—m; maize—e.
A7	2400–2600	Soybean—m; sugar beet—l; maize—m; sorghum—e.
A8	2600–2800	Soybean—ml; maize—ml; sorghum—m.
A9	2800–3000	Soybean—l; maize—l; sorghum—l.
Б1	2500–2700	Rice—e.
Б2	2700–2900	Rice—m.
Б3	2900–3300	Rice—m; cotton—e.
Б4	3300–3600	Cotton—m.
Б5	3600–4000	Cotton—l.

Based on the assessment of moisture availability and the aridity of the growing season, the boundaries of dry (rainfed) agriculture are determined. According to our studies, the southern boundary of rainfed farming in Kazakhstan corresponds to the isolines K = 0.50 [25,45].

Based on the analysis of long-term data, we propose the following criteria for assessing the conditions of rainfed agriculture:

– Good when K > 1.00 (optimal and sustainable moisture availability).
– Satisfactory when K = 0.80–0.99 (sufficient but not sustainable water availability).
– Bad when K = 0.60–0.79 (insufficient moisture availability). In these conditions, rainfed agriculture is risky, and in unfavorable years, additional irrigation is required.
– Very bad when K < 0.60 (moderate or severe moisture deficit). Rainfed agriculture is impossible.

An additional criterion is the aridity of the growing season. Rainfed agriculture is possible with an average value of HTC > 0.80 (arid conditions). Rainfed agriculture is risky with an average value of HTC = 0.60–0.79 (slightly arid). Rainfed agriculture is impossible with a stable HTC < 0.60 (moderately or severely arid).

2.3.5. Creation of Agro-Climatic Maps

The ArcGIS 10.7 software was used to create agro-climatic maps [46,47]. The “Spline” tool, located in the “Spatial Analyst” toolbox, was used to interpolate data from meteorological stations using a two-dimensional spline method with curvature minimization. This method allowed for smoothing the raster surface, which was then classified into zones. At the final stage, raster data were converted into vector format using polygonal and linear types. All collected spatial materials were presented in cartographic form. The maps were prepared at a scale of 1:6,000,000, with a resolution of 400 dpi.

3. Results and Discussion

3.1. Duration of Vegetation Period

Based on the research, we conducted zoning of the territory of Northern Kazakhstan according to the duration of the growing season. For the beginning of the growing season of spring crops, the stable air temperature transition date through 10 °C was used. In the south of Northern Kazakhstan, air temperatures steadily passed through 10 °C in spring on 20 April; in autumn, they held around this value on 2 October. In the central part of the region, air temperatures steadily passed through 10 °C in spring on 1 May; in autumn, they held around this value on 25 September. In the north of the region, the air temperature steadily passed through 10 °C in spring on 5 May, and in autumn, on 20 September (Figure 3).

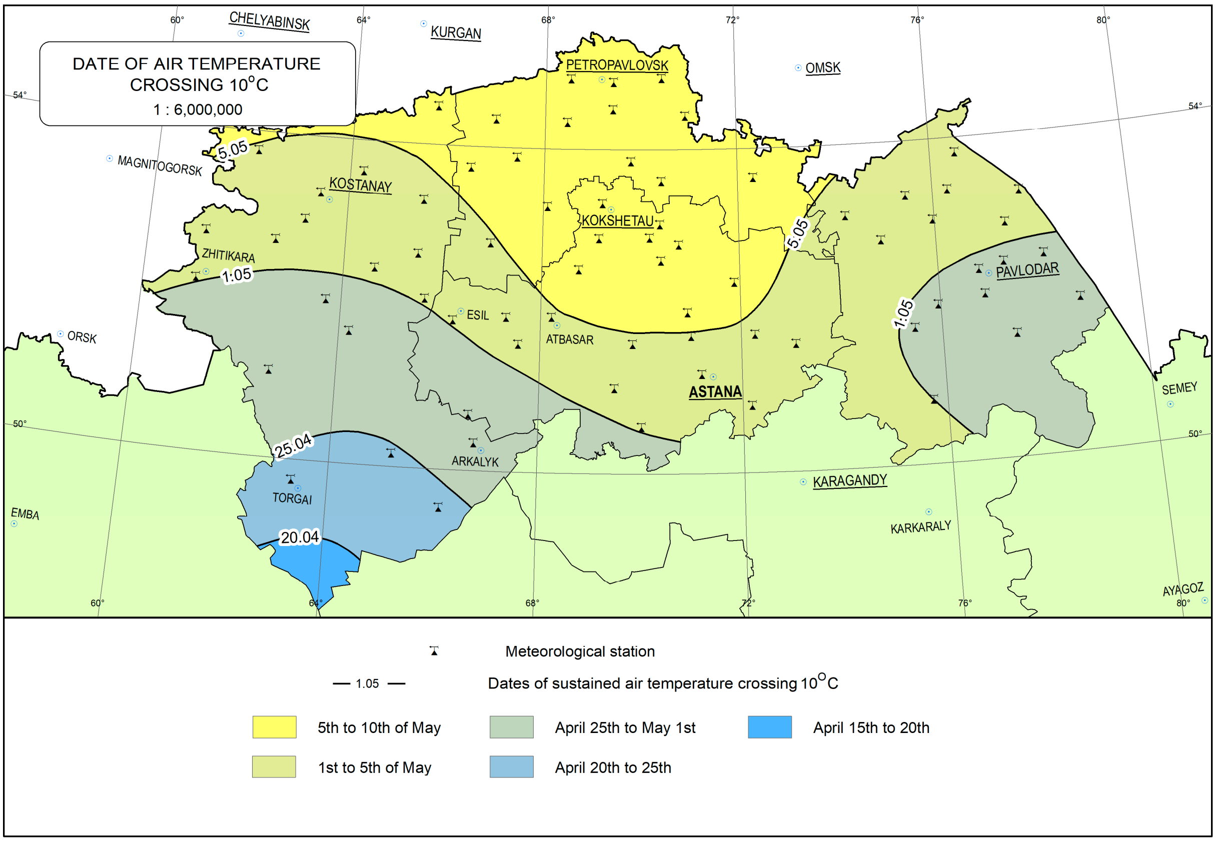

Figure 3. Transition date of mean daily air temperature through 10 °C during spring in Northern Kazakhstan.

The duration of the vegetation period (Nt > 10) is 130 days in the north of the region, 145 days in the central part, and 170 days in the south. In the north of the Akmola region, specifically in the area of upland Kokshetau, the duration is 130–135 days. In the south of the Pavlodar region, specifically in the area of upland Bayanauyl, the duration is 140–145 days (Figure 4).

3.2. Heat Availability of Vegetation Period

Within the framework of this study, we zoned the territory of Northern Kazakhstan according to the heat availability of the growing season.

Heat resources ($\sum t > 10$) in the north of Northern Kazakhstan amount to 2200 °C; in the central part, 2500 °C; and in the south, 3400 °C. In the area of upland Kokshetau, the sum of the temperatures ranged within 2000–2200 °C. In the south of the Pavlodar region, specifically in the area of upland Bayanauyl, the sum of temperatures ranged within 2000–2400 °C (Figure 5).

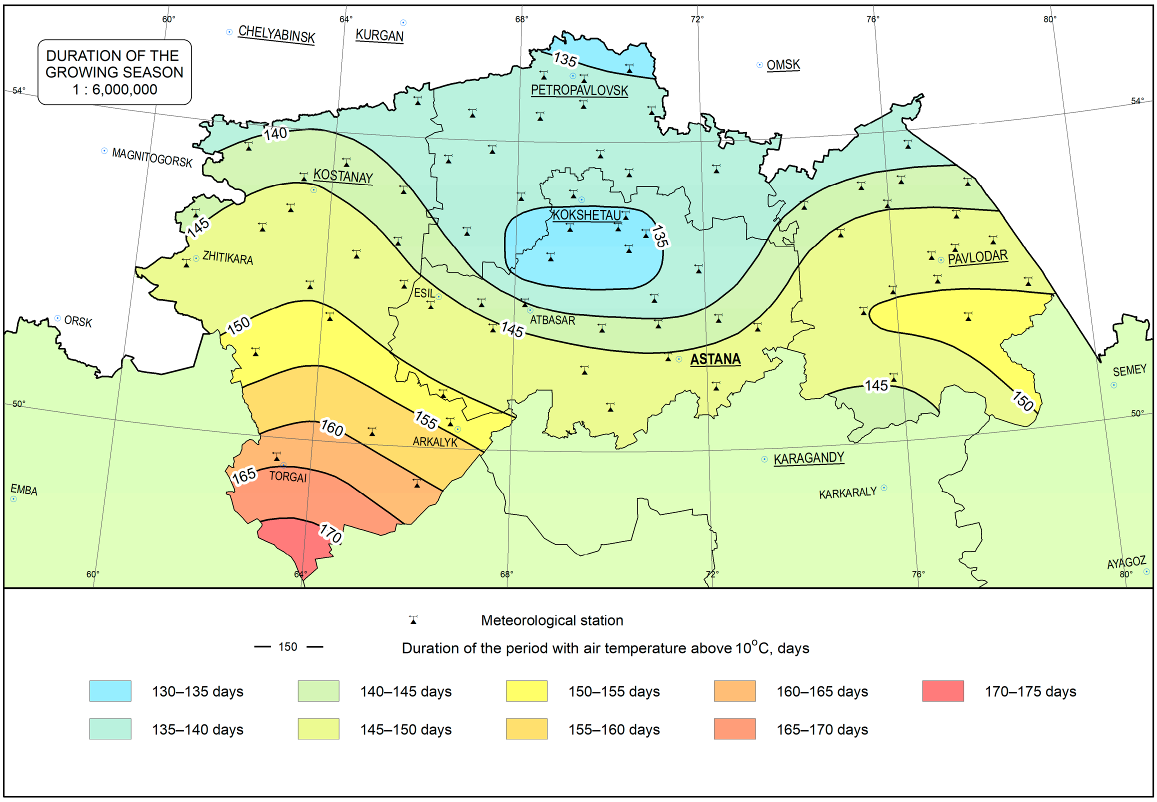

Figure 4. Duration of vegetation period in Northern Kazakhstan.

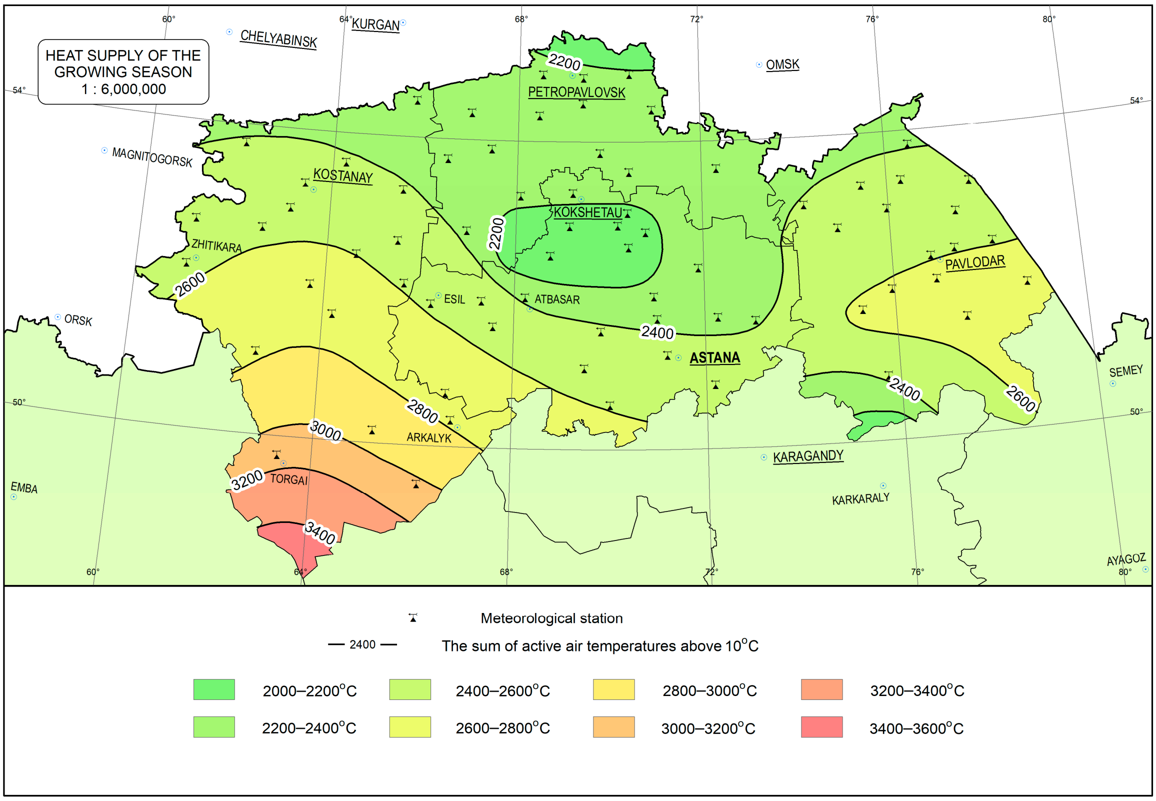

Figure 5. Heat availability of growing season in Northern Kazakhstan.

The analysis showed that over the last 33 years, there has been an increasing trend with respect to the sum of air temperatures, which means an increase in heat resources. The coefficient of determination (R^2) of the trend line for the air temperature sum series is 0.0765–0.1532 (R = 0.28–0.39), which characterizes a weak relationship. The trend in temperature change is statistically significant in the Kostanay and Pavlodar regions.

High air temperatures were observed in 1991, 1998, 2004, 2010, 2012, 2021, and 2023; the relatively cool years were 1992, 2002, 2009, 2023, and 2018 (Figure 6A).

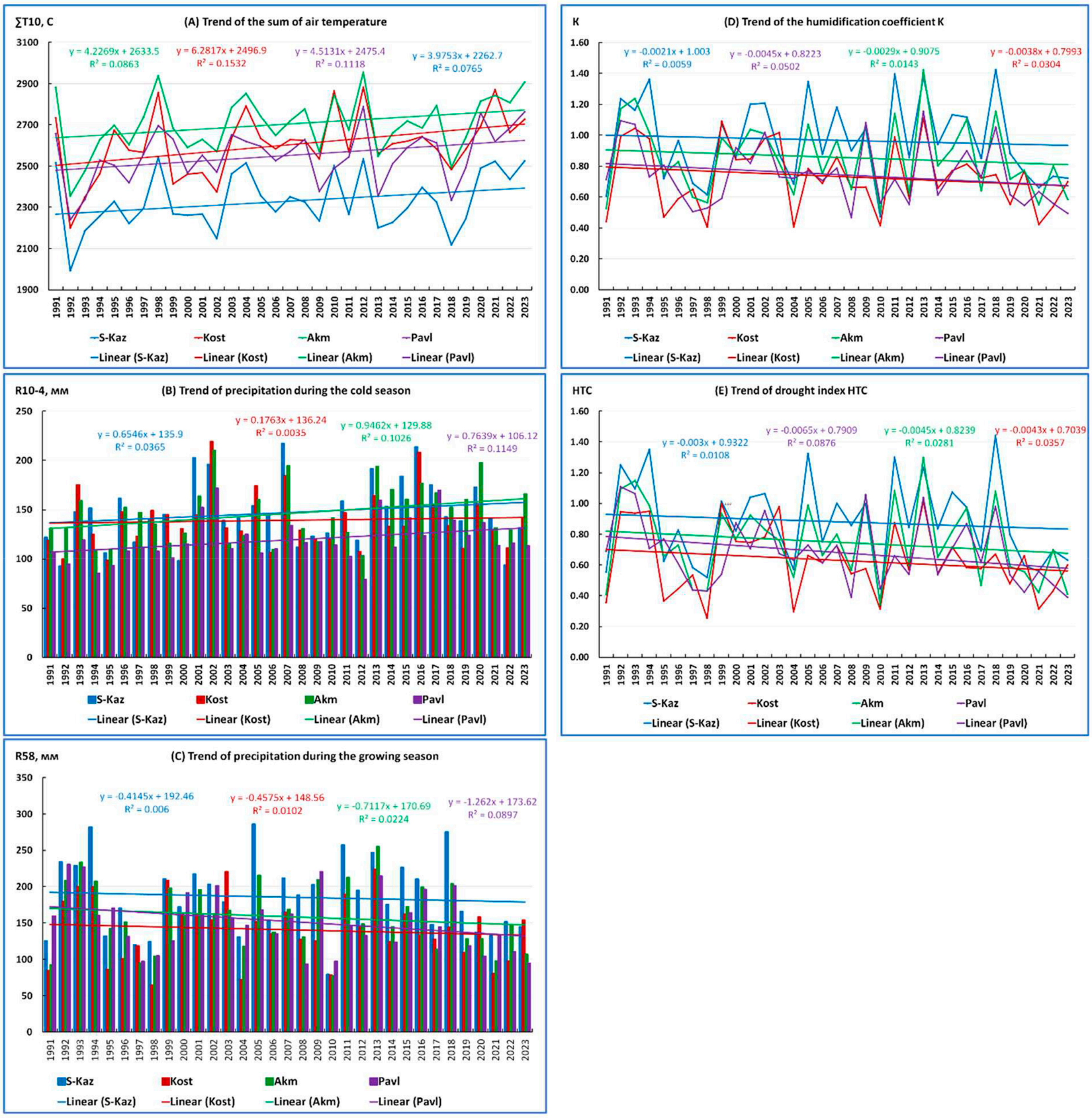

Figure 6. Precipitation and temperature trends: (**A**) trend in sum of air temperature; (**B**) trend in precipitation during cold season; (**C**) trend in precipitation during growing season; (**D**) trend in humidification coefficient K; (**E**) trend in drought index HTC.

3.3. Moisture Availability During Growing Season

The moisture availability of the growing season in Northern Kazakhstan was assessed. The annual rainfall is about 350 mm in the north of Northern Kazakhstan, 250–300 mm in the central part, and about 200 mm in the south. The greatest amount of precipitation was observed in the area of the upland Kokshetau (400–450 mm). Approximately 350 mm of precipitation per year was observed in the upland Bayanauyl area. The highest precipitation was observed in July (40–70 mm), and the lowest was observed in February (10–20 mm). During the warm period of the year, precipitation is 2–3 times higher than during the cold period.

For agricultural crops, precipitation during their active vegetation period (from sowing to maturity), i.e., May–August, is particularly important. Precipitation during the cold period of the year (October–April), which determines the amount of spring moisture reserves in the soil, is also important.

In October–April, 140–160 mm of precipitation was observed in the north of Northern Kazakhstan; in the central part, 120–150 mm was observed; and in the south, 100–120 mm was observed. In May–August, 180–200 mm of precipitation was observed in the north, 140–160 mm was observed in the central part, and 60–80 mm was observed in the south. In the area of upland Kokshetau, approximately 200 mm of precipitation was observed in May–August months, and in the area of upland Bayanauyl, approximately 190 mm was observed.

Analyses of long-term dynamics showed that for the last 33 years, there has been a tendency for precipitation to increase during the cold season and a tendency for it to decrease during the growing season (Figure 6B,C). This indicates a possibility for an increase in spring moisture reserves in the soil and a reduction in moisture availability during the growing season. The coefficient of determination (R^2) of the trend line for the series of precipitation amounts for the cold season is 0.0035–0.1149 (R = 0.06–0.34), which characterizes a weak relationship. The precipitation trend is statistically significant only in the Pavlodar region. The coefficient of determination (R^2) of the trend line for the series of precipitation amounts for the growing season is 0.006–0.0897 (R = 0.08–0.30), which characterizes a weak relationship. The precipitation trend is not statistically significant in all four regions.

During the growing season, low rainfall was observed in 1991, 1997, 1998, 2004, 2010, and 2021–2023. Heavy rainfall was observed in 1992, 1993, 2005, 2009, 2011, 2013, and 2018 (Figure 6C).

Figure 7 shows the spatial distribution of the average values of the coefficient K, which characterizes moisture availability during the growing season of spring crops.

The moisture availability of the growing season is characterized as "optimal and sustainable" ($K \geq 1.00$) and "sufficient, but not sustainable" (K = 0.80–0.99) in the northern and central parts of Northern Kazakhstan; in the southwest and southeast, there is "insufficient moisture availability" (K = 0.60–0.79); and in the extreme southeast, there is a "moderate moisture deficit" (K = 0.40–0.59) (Figure 7).

The analysis of multi-year dynamics showed that for the last 33 years, there has been a decreasing moisture coefficient K value (Figure 6D), which means a decrease in moisture availability during the growing season. The coefficient of determination (R^2) of the trend line for the series of moisture coefficient K is 0.0060–0.0502 (R = 0.08–0.22), which characterizes a weak relationship. The K trend is not statistically significant in all four regions.

3.4. Aridity of Growing Season

Within the framework of this study, we zoned the territory of Northern Kazakhstan according to the dryness of the growing season.

The growing season of the northern and central parts of Northern Kazakhstan is characterized as "not arid" ($HTC \geq 0.80$) and "slightly arid" (HTC = 0.60–0.79); the southwest and southeast are characterized as "moderately arid" (HTC = 0.40–0.59); and the extreme southeast (HTC = 0.20–0.39) is characterized as "severely arid" (Figure 8).

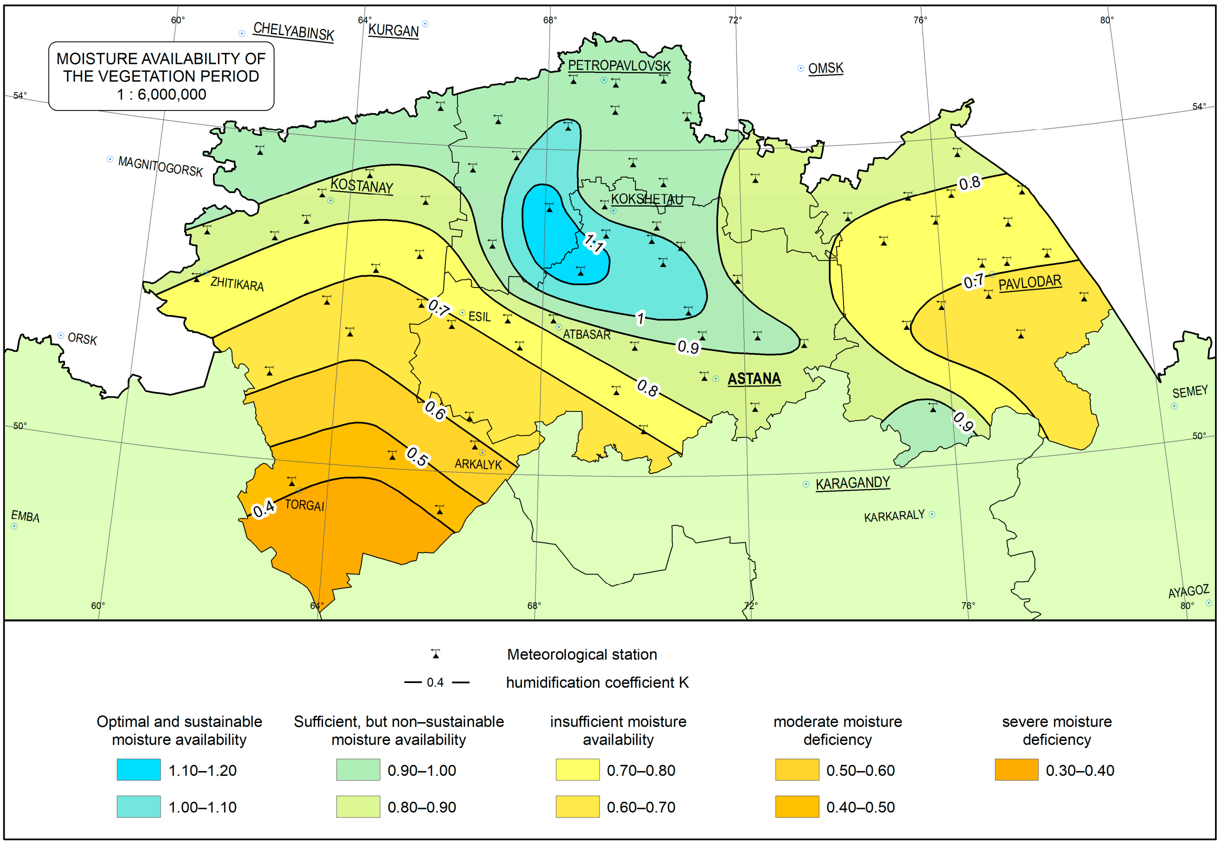

Figure 7. Moisture availability during vegetation season in Northern Kazakhstan.

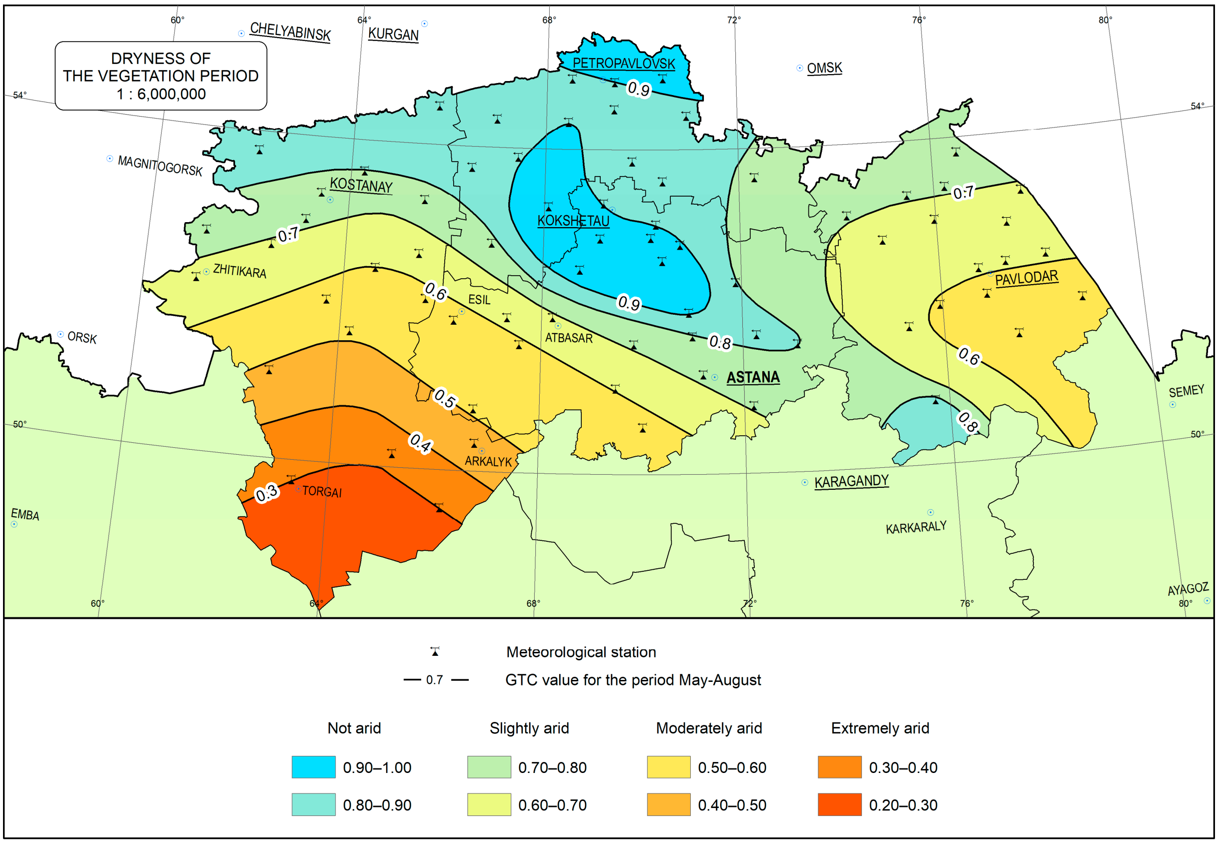

Figure 8. Dryness of growing season in Northern Kazakhstan.

The analysis of multi-year dynamics showed that for the last 33 years, there has been a decreasing drought index HTC value, which means an increase in the dryness of the growing season (Figure 6E). The coefficient of determination (R^2) of the trend line for the series of drought index HTC is 0.006–0.0876 (R = 0.08–0.30), which characterizes a weak relationship. The trend of HTC is not statistically significant in all four areas.

3.5. Agro-Climatic Zoning of Territory of Northern Kazakhstan

Based on the assessment of the heat and moisture availability of the growing season, the agro-climatic zoning of the territory of Northern Kazakhstan was carried out. There are five agro-climatic zones in the territory of Northern Kazakhstan (Figure 9).

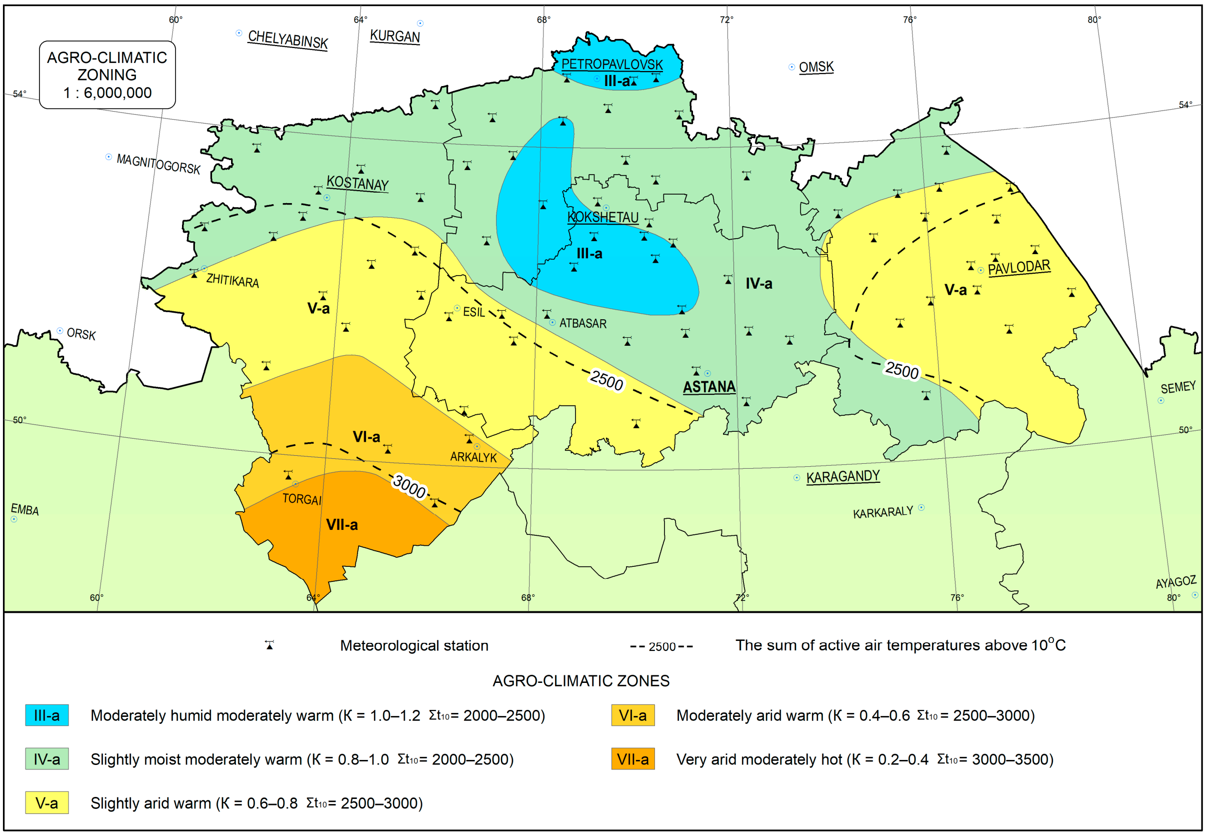

Figure 9. Agro-climatic zoning of Northern Kazakhstan.

Zone III-a, which is "Moderately humid moderately warm", occupies the northern edge of the North Kazakhstan region, as well as the territory of upland Kokshetau.

Zone IV-a, which is "Slightly humid moderately warm", occupies the northern part of the Kostanay region, the main territory of the Severo-Kazakhstan region, the central and northern parts of the Akmola region, and the northern and southwestern outskirts of the Pavlodar region.

Zone V-a, which is "Slightly arid warm", occupies the southern part of the northern half of the Kostanay region, the southwestern outskirts of the Severo-Kazakhstan region, the south-western part of the Akmola region, and the central and southeastern parts of the Pavlodar region.

Zone VI-a, which is "Moderately arid warm", occupies the northern part of the southern half of the Kostanay region.

Zone VII-a, which is "Very arid moderately hot", occupies the southern edge of the Kostanay region.

The area is occupied by Zone III-a at 9%; IV-a at 41%; V-a at 36%; VI-a at 9%; and VII-a at 5% of the territory of Northern Kazakhstan.

3.6. Crop Zoning

Based on the assessment of heat availability during the growing season, we conducted zoning of the 25 main crops in accordance with the agro-climatic zones of Northern Kazakhstan. Based on moisture availability and dryness of the vegetation period, the conditions for rainfed farming were estimated.

In agro-climatic Zone III-a, ordinary chernozems prevail (carbonate, solonetz, and underdeveloped); there are also meadow–chernozem soils and malt soils. The humus content of chernozems is 6–8%.

In Zone IV-a, southern chernozems (carbonate and solonetz) prevail; there are also ordinary chernozems, meadow–chernozem soils, malt, and solonetz. The humus content of chernozems is 4–6%.

Dark chestnut soils (carbonate and solonetz), medium chestnut soils (carbonate and solonetz), and solonetz prevail in Zone V-a. The humus content of chestnut soils is 2.5–4.5%.

Medium chestnut (carbonate and solonetz) soils, light chestnut (solonetz) soils, and solonetz prevail in Zone VI-a. The humus content of chestnut soils is 2–3%.

Solonetz and brown desert (solonetz) and light chestnut (solonetz) soils prevail in Zone VII-a. The humus content of brown soils is 1–2%.

Thermal resources of the territory determine the possibility of growing agricultural crops. In Northern Kazakhstan, the list of agricultural crops provided with heat is expanding from the north to the south.

According to our calculations, the following agricultural crops are obtained when temperatures rise: in agro-climatic Zone III-a, crops of group A1–A4 (buckwheat; barley; oats; peas; potatoes; cucumbers; wheat; beans; pravin; lentils; chickpea; lupin; oilseed–flax; long-lasting flax; cabbage; tomatoes; millet; chickpeas; sunflower—e; canola—e); in Zone IV-a, crops of group A1–A6 (+ lupin; sunflower; canola; soybean—e; sugar beet—m; maize—e); in Zone V-a, crops of group A1–A8 (+ sugar beet; soybean—ml; maize—ml; sorghum—m); and in Zones VI-a and VII-a, crops of group A1–A9 (+ soybean—l; maize—l; sorghum—l) (Table 6).

Humidification by precipitation determines the possibility of conducting rainfed agriculture. In Northern Kazakhstan, good conditions for rainfed agriculture were created in agro-climatic Zone III-a; satisfactory conditions were created in Zone IV-a; and poor conditions were created in Zone VI-a. Rainfed farming is impossible in agro-climatic Zones VI-a and VII-a, i.e., additional irrigation of agricultural fields is required here (Table 7).

Table 7. Crop zoning based on heat and moisture availability.

Group	Name of Zone	Crop Group Supplied with Heat	Condition for Rainfed Farming
III-a	Moderately humid moderately warm	A1–A4	Good
IV-a	Slightly humid moderately warm	A1–A6	Satisfactory
V-a	Slightly arid warm	A1–A8	Poor
VI-a	Moderately arid warm	A1–A9	Impossible
VII-a	Very arid moderately hot	A1–A9	Impossible

4. Conclusions

Based on meteorological data for 1991–2023, agro-climatic indicators of heat availability, moisture availability, and dryness of the growing season were established. Maps of the spatial distribution of agro-climatic indicators were created. The agro-climatic zoning of the territory of Northern Kazakhstan with respect to heat and moisture availability was conducted. Zoning of the 25 main agricultural crops was carried out in accordance with agro-climatic zones.

The vegetation period of spring grain crops, on average, begins in the south of Northern Kazakhstan on May 10, and in the north, it begins on 15 May. The duration of the vegetation period in the north of the region is 90–105 days; in the central part, it is 85–95 days; and in the south, it is 80–90 days. Thermal resources in the north of the region measure at 2200 °C; in the central part, they measure at 2500 °C; and in the south, they measure at 3400 °C. Annual precipitation is about 320–340 mm in the north of the region, 250–300 mm in the central part, and about 200 mm in the south. In May–August, in the north, 160–170 mm of precipitation was observed, 140–160 mm was observed in the central part, and 60–80 mm was observed in the south.

Moisture availability during the growing season is characterized in the northern and central parts of Northern Kazakhstan as "optimal and sustainable", and in the extreme southeast, it is characterized as "moderate moisture deficit".

The dryness of the growing season is characterized in the northern and central parts of Northern Kazakhstan as "not arid", and in the extreme southeast, it is characterized as "severely arid".

The territory of Northern Kazakhstan is divided into five agro-climatic zones.

According to the agro-climatic zones of Northern Kazakhstan, the zoning of agricultural crops was carried out in accordance with their need for heat.

In Northern Kazakhstan, rainfed farming is impossible in agro-climatic Zones VI-a and VII-a.

The obtained research results will be useful for agriculture in Northern Kazakhstan and contribute to the development of climate-oriented agricultural technologies, providing more complete knowledge of the climatic resources of the territory in scientific research and in practice. This study's results can be used in the reasonable planning and carrying out of agro-technical measures in optimal terms and the development of strategic plans for crop production development.

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