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Assessment of agroclimatic resources in agricultural landscapes of the Turkestan region of the Republic of Kazakhstan

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Highlights:
- Climatic indicators are used to assess agroclimatic resources of landscapes.
- The use of complex methods of forecasting climate productivity for a long time.
- Research methods are based on classical, modern methods of mathematical statistics.
- The agroclimatic resources model accurately forecasts climate productivity.
- The agroclimatic resources model is based on 15 natural system climatic indicators.

Abstract: The article presents the scientific results of a study assessing agroclimatic resources in agricultural landscapes located in various natural zones of the Turkestan region of the RK (Republic of Kazakhstan). The research methods included classical and modern methods of mathematical statistics using digital technology and time series graphs to develop a mathematical model for climatic and hydrological indicators. Assessment of changes in indicators of agroclimatic resources in agricultural landscapes for 1941–2020 showed that the sum of air temperature, evaporation from the water surface and radiation balance of the daytime surface, characterising the energy resources of landscapes, increased by 10–15%, which contributes to increase in the total water consumption of agricultural land by 10–12%. Meanwhile, the decreasing tendency of the amount of precipitation by 5–10% in all natural climatic zones of the region has become one of the factors leading to a decrease in the natural moisture supply of the soil and vegetation cover of landscapes by 10–15%, acting as important environment-forming and ecological functions. The combined impact of these environment-forming factors has become the key reason for the increase in the deficit of agricultural land water consumption by 15–20%, the reduction of solar energy costs for the soil-forming process by 10–15% and the increase of the climate aridisation, and has become a signal for the need in the safety of agricultural activities, requiring the development of a set of adaptive measures to mitigate this process in the region.

Keywords: agroclimatic resources, air temperature, climate aridisation, heat supply, landscapes, moisture supply, natural zones

INTRODUCTION

The climatic resources of the Turkestan region are one of the key natural factors that determine the conditions for the development of agriculture. Development of agriculture requires the rational distribution of its branches across the territory based on the analysis of agroclimatic resources, which makes it possible to determine the compliance of the climate of a specific territory with the basic requirements for the growth of agricultural crops, to establish the specialisation of agricultural formations and determine the overall agricultural production.

Based on the concept of agroclimatic resources, the form of their presentation as integral indicators is also determined, which allows a quantitative and qualitative assessment of the resource potential of the natural environment to address problems of optimising the territorial organisation of agricultural production, developing a scheme for sustainable nature management and designing rational types of agricultural landscapes.

Fundamental scientific research by scientists in the fields of climatology, agrolandscape science and agricultural nature management formed the core of the knowledge base for assessment of agroclimatic resources. In particular, Rychko (1996) put forward the concept of the systemic impact of hydrometeorological factors and indicators on heat exchange processes, hydrothermal elements of the natural system and built physical-bio-statistical models of the formation and transformation of agroclimatic resources in agricultural landscapes.

The geographic distribution of crops is mainly governed by various climatic elements. Temperature, water, and solar radiation are key climatic parameters which condition net photosynthesis and allow crops to accumulate dry matter according to the rates and patterns which are specific to individual crop species (Fischer and Heilig, 1997).

One of the fundamental directions in the assessment of agroclimatic resources is the direction developed in the works of Fischer and Heilig (1997), dealing with the problem of population development with estimates of the availability of land and water resources.

Zhukov (1998) proposed a fundamentally new approach to the assessment of agroclimatic resources for the cultivation of specific crops, which implements the idea of a consistent assessment of the existing weather situation every ten days and its compliance with crop requirements, reduction of yield in abnormal years and their probable interpretation in a long-term context.

Finding the level of intensity of agriculture that corresponds to the natural conditions of the territory is an important prerequisite for justification of the optimal location of crop and livestock industries, which ensures the highest cost-effectiveness of production (Kovshov and Nosov, 2005).

The agro-resource potential of agricultural development territory, based on its structural and functional organisation, should be assessed on the basis of a system-functional approach according to the resultant method, that is, by the volume of crop production in unified (grain, fodder, energy) units. Thus, the productive capacity of strategic resources at different levels of their functioning (extensive, common, intensive and high technologies) is subject to assessment (Sukhanov, 2013). At the same time, it should be noted that the analysis of land suitability (Ahamed, Rao and Murthy, 2000), as well as the analysis of annual air temperature and the period of precipitation, are a necessary condition for organising regional agricultural activities (Mustafayev *et al*., 2023). Land suitability assessment (LSA) is a valuable tool for land use planning in major countries of the world (Olaniyi *et al*., 2015). Suitability of land is assessed considering rational cropping system, for optimising the use of a piece of land for a specific use (Mustafa *et al*., 2011). Potential toxic element (PTE) pollution in the soil is a major threat to global soil health (Li *et al*., 2023). Therefore, rational planning of land types and the reduction of landscape fragmentation could reduce the risk of soil erosion (Wen *et al*., 2023). The works of Li *et al.* (2023) and Wen *et al.* (2023) show the impact of pollution and soil erosion in river basin catchments on the resource potential and productivity of agricultural landscapes, as well as the well-being of the population.

Agroclimatic constraints originate primarily due to climate, and cause direct or indirect losses in the yield and quality of produce (Fischer *et al*., 2002). Since the development of agricultural and natural resources research, the climate has been of primary concern because of its impact on food, feed, and fibre production (Steiner and Hatfield, 2008). Global warming will lead to higher temperatures and changes in the rainfall pattern, and this in turn will modify the extent and productivity of land suitable for agriculture (Fischer *et al*., 2006; Kulshreshtha, 2011). Under the context of global warming, Central Asia has experienced profound climate warming since the 20th century, much faster than the global land average (Fan *et al*., 2023). Warming of more than 3°C would have negative impacts in all regions (Zhai and Zhuang, 2009).

Developing countries are more vulnerable to climate change than developed countries, because of the predominance of agriculture in their economies, the scarcity of capital for adaptation measures, their warmer baseline climates and their heightened exposure to extreme events, such as drought (Fischer *et al*., 2005; Lee *et al*., 2023), cause agricultural production accounts for the largest share of food supplies and provides several ecosystem services (e.g., food provisioning) (Rahman *et al*., 2022; Kazemi Garajeh *et al*., 2023). Kafatos *et al.* (2017) indicate that the study of similar geographic and climate regions, but with very different socio-economic conditions in the mid-latitude region, can yield important clues to resilience in a changing climate, when subject to uncertain conditions of socioeconomic evolution. High climate variability in arid and semi-arid regions of developing countries makes farming a very risky business and climate risk management in these areas may include the prediction of the likely weather-related hazards as well as determining the measures that can be used to minimise that risk to a level that can be managed (Moeletsi and Walker, 2012). Osborne *et al.* (2022) propose focusing on the controls and consequences of two key characteristics affecting dryland biogeochemistry: (1) high spatial and temporal heterogeneity in environmental conditions and (2) generalised resource scarcity. In this regard, pasture management has positive effects on land sustainability, maintaining the landscape and cultural value, and supporting biodiversity and soil fertility, thereby reducing soil loss and natural risks (Casale and Bocchiola, 2022).

FAO (2013) proposes climate-smart agriculture as a strategy to adapt and build resilience to climate change and to reduce agricultural greenhouse gases (GHGs) while maintaining high yields and ensuring food security (Lipper *et al*., 2014; Tekeste, 2021). Daily *et al.* (2009) consider that relative to other forms of capital, landscape is often poorly understood, rarely monitored, and undergoing rapid degradation, because all humanly used resources are embedded in complex, social-ecological systems (SESs) (Ostrom, 2009). Gains in productivity and predictability of agricultural production by the conversion of "natural" landscape elements and loss of ecosystem services (ES) are a source of stakeholders' conflicts (Laterra, Orúe and Booman, 2012). Consequently, landscape policies must be formulated to fit in with the objectives of sustainable development (Jones, 2019).

It is a natural feature of agricultural landscapes that they function within a changing environment, however, only a few studies at regional and continental scales have assessed their capacity in spatial and temporal aspects to determine their potential to provide ecosystem services (Bolliger and Kienast, 2010). Based on the recommendations of the Food and Agriculture Organization (FAO, no date) for the assessment of the environmental services of landscapes, the possibility of using a fuzzy (partial) affiliation model based on GIS technology has been proven to assess the suitability of arable land, allowing for optimal use of available land resources for sustainable agricultural production (Ahamed, Rao and Murthy, 2000). Based on the development and deepening of the concept of environmental services, known in environmental economics, Mustafayev, Tursynbaev and Kireycheva (2022) propose a system of mathematical models that include integral indicators of anthropogenic activity to assess the level of natural environmental and anthropogenic services during the reclamation of agricultural land for the purpose of rational and efficient use of their natural resource potential and identifying their regional differences.

In this aspect, the study of agroclimatic resources in agricultural landscapes located in various natural zones of the Turkestan region of the Republic of Kazakhstan (RK) using a systematic approach based on the environmental concept of the activity of soil and vegetation cover, allows to conduct a multi-criteria assessment of the agro-resource potential of the natural environment.

The region is located in the southern part of the RK. The following natural zones of the Turkestan region are distinguished on the territory of the region with an area of 116 280 km^2 (4.3% of the territory of the RK).

The purpose of the study is to establish a pattern of formation and territorial transformation of agroclimatic resources in the Turkestan region of the RK as a scientific and theoretical basis for their assessment of agricultural landscapes (Fig. 1).

MATERIALS AND METHODS

The study of agroclimatic resources in the agricultural landscapes of the Turkestan region was carried out across natural zones based on long-term climatic indicators of the Republican State Enterprise (RSE) "Kazhydromet" (Rus. Respublikanskoe Gosudarstvennoe Predpriyatie "Kazgidromet") (Kazgidromet, 2022), the World Meteorological Organization (WMO, no date) and "Weather and Climate" reference-information portal for 1941–2020 (Spravochno-informatsionnyy portal "Pogoda i klimat", no date). The initial information for the allocation of natural areas of the Turkestan region includes materials of the field landscape, research of contributors and a landscape map of the RK.

Assessment of agroclimatic resources in agricultural landscapes should be based on the environment-forming or ecological functions of the climate at various stages of its development. However, the methods for assessing agroclimatic resources and

Fig. 1. Turkestan region of the RK; source: Esri, Maxar, Earthstar Geographics and the GIS User Community

the forms of their presentation have changed significantly depending on the level of knowledge, worldviews and the emergence of new knowledge about natural processes, which are formed on the basis of natural science ideas about the mechanisms of qualitative and quantitative assessment of the resource potential of the natural environment.

The methodology of the study is based on identifying the dependence of the obtained quantitative and qualitative indicators characterising the balance of energy inflow and outflow, in other words, it is based on the law of energy conservation, which contains the following estimated indicators: energy resources, moisture and heat supply, and climate aridisation, which in general determine the development trend of agricultural production.

Energy resources (heat supply) determine the following indicators.

1) Sum of biologically active air temperatures above 10°C ($\Sigma SBCT_i$ > 10°C), which is calculated using the Equation (1) (Mustafayev and Ryabtsev, 2012):

$$\sum SBCT_i > 10^{\circ}\mathrm{C} = \sum_{i=1}^{n} AMT_i\ N_i \tag{1}$$

where: AMT_i = average monthly air temperature above 10 (°C), N_i = number of days in a month; n – number of months where the average monthly air temperature is above 10°C; $\Sigma SBCT_i$ when <1500°C – very low (1 point), 1500–2000°C – low (2 points), 2001–2800°C – average (3 points), 2801–3200°C – above average (4 points), 3201–4500°C – increased (5 points), 4501–5200°C – high (6 points), when >5200°C – very high (7 points).

2) Surface radiation balance of air and soil (RB_i), which is determined using the Equation (2) (Nikolsky and Shabanov, 1986):

$$RB_i = 4.1868[13.39 + 0.0079 \sum SBCT_i > 10^{\circ}\mathrm{C}] \tag{2}$$

their estimated indicators: 4.1868 = conversion factor from kcal·cm^{-2} to kJ·cm^{-2}, when <100.0 kJ·cm^{-2} – very low (1 point), 100.0–120.0 kJ·cm^{-2} – low (2 points), 121.0–145.0 kJ·cm^{-2} – average (3 points), 146.0–162.0 kJ·cm^{-2} – above average (4 points), 163.0–205.0 – increased (5 points), 206.0–230.0 kJ·cm^{-2} – high (6 points), when >230.0 kJ·cm^{-2} – very high (7 points).

3) Average monthly evapotranspiration (AME_i) and total evapotranspiration in the biologically active period of the year (TEB_i), which is calculated using the Equation (3) (Ivanov, 1941):

$$\begin{gathered} AME_i = (AMT_i + 25)^2(100 - AMRH_i) \\ \text{and } TEB_i = \textstyle\sum_{i=1}^{n} AME_i \end{gathered} \tag{3}$$

where: $AMRH_i$ – average monthly relative air humidity (%); their estimated indicators: when <200 mm – very low (1 point), 200–400 mm – low (2 points), 401–800 mm – average (3 points), 801–1200 mm – above average (4 points), 1201–1400 mm – increased (5 points), 1401–1600 mm – high (6 points), when >1600 mm – very high (7 points).

4) Total water consumption of agricultural land (ET_i), which is calculated using the Equation (4) (Budyko, 1956):

$$ET_i = 10R_i/L \tag{4}$$

where: L = latent heat of evaporation, numerically equal to 2.5 kJ·cm^{-3}. Estimated indicators: when: <100 mm – very low (1 point), 100–250 mm – low (2 points), 251–500 mm – average (3 points), 501–750 mm – above average (4 points), 751–1000 mm – increased (5 points), 1001–1250 mm – high (6 points), when >1250 mm – very high (7 points).

5) Solar energy expenditure for the soil-forming process in natural zones (ESF_i) is determined using the Equation (5) (Volobuev, 1974):

$$ESF_i = RB_i \exp(-\alpha\, \bar{R}_i) \tag{5}$$

where: α = indicator of the complete use of radiation energy in soil-forming processes, numerically equal to 0.47, $\bar{R}_i$ = "radiation index of dryness" or complex hydrothermal coefficient, ESF_i when <10 kJ·cm^{-2} – very low (1 point), 10–50 kJ·cm^{-2} – low (2 points), 51–90 kJ·cm^{-2} – average (3 points), 91–130 kJ·cm^{-2} – above average (4 points), 131–160 kJ·cm^{-2} – increased (5 points), 161–200 kJ·cm^{-2} – high (6 points), when >200 kJ·cm^{-2} – very high (7 points).

When calculating the natural moisture supply, the following indicators were considered.

1) Natural moisture content (NMC_i) was determined using the Equation 6 (Ivanov, 1941):

$$NMC_i = AAP_i/TEB_i \tag{6}$$

where: AAP_i = annual precipitation (mm); its estimated indicators: when <0.12 – very dry (1 point), 0.12–0.21 – dry (2 points), 0.22–0.43 – semi-arid (3 points), 0.44–0.76 – arid (4 points), 0.77–1.00 – semi-humid (5 points), 1.01–1.16 – humid (6 points), >1.16 – excessively humid (7 points).

2) Radiation index of dryness ($\bar{R}_i$), which is the ratio of radiation balance (RB_i) and heat consumption for the evaporation of precipitation ($L \cdot AAP_i$), was calculated using the Equation (7) (Budyko, 1956):

$$\bar{R}_i = RB_i/(L \cdot AAP_i) \tag{7}$$

where: L = latent heat of evaporation, numerically equal to 2.5 kJ·cm^{-2}, which, firstly, considers the idea of moistening and the position on the value of the ratio of the radiation balance and precipitation to characterise the moistening conditions, secondly, it characterises the conditions of heat and moisture supply of soil and vegetation cover, thirdly, it largely determines the conditions for the formation of soil, hydrogeological, and geochemical conditions, and, fourthly, it makes it possible to consider the nature and intensity of human anthropogenic activity. Its estimated indicators are: when <0.80 – excessive moisture (7 points), 0.80–1.00 – optimal moisture (6 points), 1.01–1.20 – average moisture (5 points), 1.21–1.80 – moderately insufficient moisture (4 points), 1.81–2.30 – insufficient moisture (3 points), 2.31–3.00 – very insufficient moisture (2 points), when >3.00 – extremely insufficient moisture (1 point).

3) Hydrothermal coefficient of G.T. Selyaninov (HTC_i) was determined using the Equation (8) (Selyaninov, 1958):

$$HTC_i = AAP_{i>10}/(0.10 \sum SBCT_i) \tag{8}$$

where: $AAP_{i>10}$ = amount of precipitation for the period with average daily air temperatures above 10°C (mm), HTC_i when <0.20 – very severe drought (1 point), 0.20–0.40 – severe drought

(2 points), 0.41–0.70 – medium drought (3 points), 0.71–1.00 – insufficient moisture (4 points), 1.01–1.40 – optimal moisture (5 points), 1.41–1.60 – increased moisture (6 points), when >1.60 – excessive moisture (7 points).

4) Bioclimatic potential (BCP_i) was calculated using the Equation (9) (Shashko and Dyuzheva, 1969):

$$BCP_i = NMC_i \left(\sum SBCT_i/1000\right) \tag{9}$$

where: 1000 = sum of biologically active temperatures (°C) above 10°C, corresponding to the modern border of the field farming; BCP_i when <1.60 – very low (1 point), 1.60–2.10 – low (2 points), 2.11–2.60 – reduced (3 points), 2.61–3.00 – average (4 points), 3.01–3.40 – increased (5 points), 3.41–3.80 – high (6 points), when >3.80 – very high (7 points).

5) Moisture index (MI_{di}) was determined using the Equation (10) (Shashko, 1985):

$$MI_{di} = AAP_i/\sum AAHD_i \tag{10}$$

where: $\Sigma AAHD_i$ = sum of air humidity deficit in the biologically active period of the year (100 Pa; 100 Pa = 1 mbar), MI_{di} when <0.05 – very dry (1 point), 0.05–0.09 – dry (2 points), 0.10–0.19 – very arid (3 points), 0.20–0.34 – arid (4 points), 0.35–0.44 – semi-humid (5 points), 0.45–0.60 – humid (6 points), when >0.60 – excessively humid (7 points).

6) Effective humidification index (HF_i) was estimated using the Equation (11) (Volobuev, 1974):

$$HF_i = 43.2\ \mathrm{lg}AAP_i - AAT_i \tag{11}$$

where: AAT_i = average annual air temperature (°C), HF_i when <70.0 – very low (1 point), 70.0–80.0 – low (2 points), 81.0–90.0 – reduced (3 points), 91.0–100.0 – average (4 points), 101.0–110.0 – increased (5 points), 111.0–120.0 – high (6 points), >120.0 – very high (7 points).

7) Climate favourable index (CL_i) was calculated using the Equation (12) (Pegov and Khomyakov, 1991):

$$\begin{aligned} CL_i = &\sqrt{\{\mathrm{arctg}[(AAT_i-6)/4]+1.57\}}\ \cdot \\ &\cdot\ \sqrt{\{\mathrm{arctg}[(HF_i-112)/4]+1.57\}} \end{aligned} \tag{12}$$

where: CL_i when <0.50 – very low (1 point), 0.50–0.65 – low (2 points), 0.66–0.75 – reduced (3 points), 0.76–0.95 – average (4 points), 0.96–1.00 – increased (5 points), 1.01–1.20 – high (6 points), >1.20 – very high (7 points).

When assessing the climate aridity, the following indicators were considered.

1) De Martonee aridity index (IA_i) was determined using the Equation (13) (De Martonne, 1926):

$$IA_i = AAP_i/(AAT_i+10) \tag{13}$$

where: IA_i when <6.0 – extremely arid (1 point), 6.0–10.0 – strongly arid (2 points), 10.1–15.0 – arid (3 points), 15.1–20.0 – slightly humid (4 points), 20.1–30.0 – medium humid (5 points), 30.1–40.0 – super humid (6 points), when >40.0 – hyper-super humid (7 points).

2) Bioclimatic index of aridity (BIA_i) was determined using the Equation (14) (Mezentsev and Karnatsevich, 1969):

$$BIA_i = (AAP_i/CE_i) = \left[AAP_i/\left(5.12\sum SBCT_i\ +306\right)\right] \tag{14}$$

where: CE_i = total evaporation for the year (mm), BIA_i when <0.14 – extremely arid (1 point), 0.14–0.28 – strongly arid (2 points), 0.29–0.43 – arid (3 points), 0.44–0.60 – sub-arid (4 points), 0.61–0.75 – moderately arid (5 points), 0.76–0.90 – slightly arid (6 points), when >0.90 – periodically arid (7 points).

3) Normalised index of aridity (NIA_i) was determined using the Equation (15) (Vinogradov, 1997):

$$NIA_i = 1 - BIA_i \tag{15}$$

where: NIA_i when <0.18 – periodically arid (7 points), 0.18–0.31 – slightly arid (6 points), 0.32–0.45 – moderately arid (5 points), 0.46–0.59 – sub-arid (4 points), 0.60–0.74 – semi-arid (3 points), 0.75–0.86 – strongly arid (2 points), when >0.86 – extremely arid (1 point).

In view of the above integral climatic and energy indicators, agroclimatic resources were determined in agricultural landscapes located in various natural zones of Turkestan region of the RK.

RESULTS AND DISCUSSION

ASSESSMENT OF ENERGY RESOURCES OF AGRICULTURAL LANDSCAPE USE

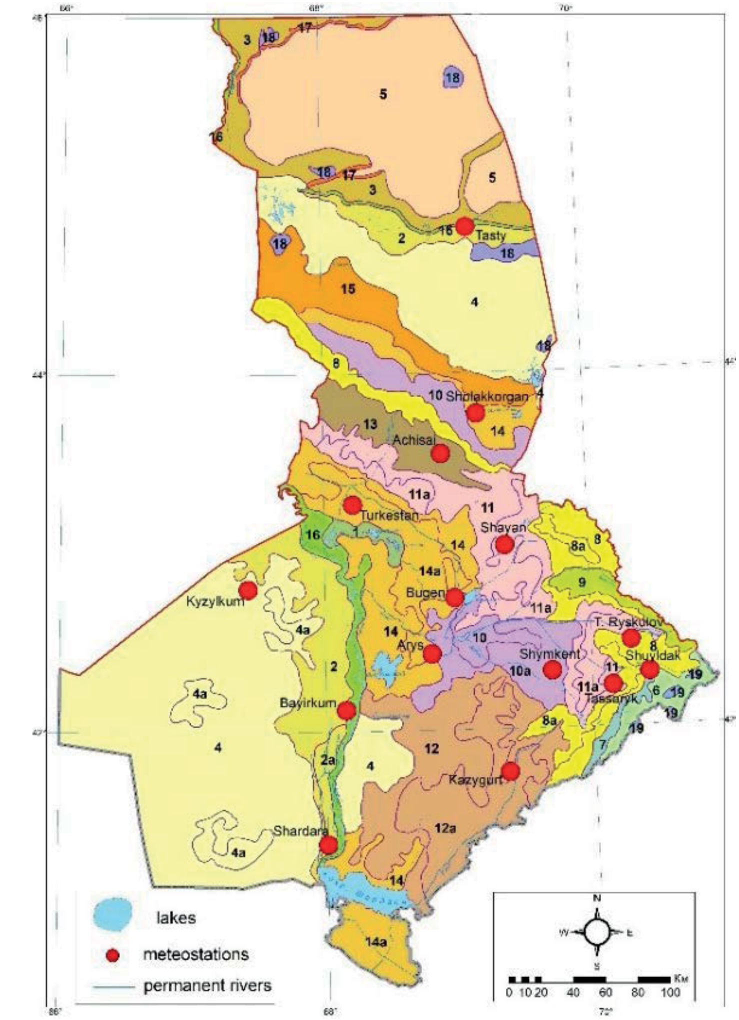
The landscapes used for agricultural production in the Turkestan region are one of the strategic resources for the food security of the RK. The natural-territorial complexes of the region with their inherent climatic features and soil determine the environment-forming value of the administrative territories of the Turkestan region and form the basis of the agro-resource potential of landscapes. It should be noted that in the Turkestan region, there are approximately 2119.0 thous. people, constituting 10.7% of the total population of the RK. Moreover, 1714.5 thousand people (80.8% of the population of the region) live in rural areas and are mainly engaged in agricultural production.

Agricultural nature management of the Turkestan region is formed in six natural zones (Fig. 2).

The agroclimatic characteristics of landscapes in natural areas used for agricultural production in the Turkestan region include the following indicators: energy resources, heat and moisture supply, and climate aridity, which form a complex triune foundation of their agroclimatic potential, which makes it possible to assess the environment-forming function of the landscape system for the purpose of rational agricultural nature management. To identify the statistical significance of changes in the energy resources of the climate in the agricultural landscapes of the Turkestan region of the RK from 1941 to 2020, a comparative analysis was performed using the data collected from 16 weather stations located in various natural zones (Fig. 3–5).

Assessment of agroclimatic indicators across natural zones (agricultural landscapes) of the Turkestan region showed that energy indicators for 1941–2020 tend to increase.

- In the mountainous area (highland, low-hill and foothill landscapes), covering most of the territory of Tolebi region,



Natural landscape boundaries

Class	Sub-class	Sort	Type: Meadow alpine and subal-pine	Forest-meadow-steppe	Steppe-dry-steppe	Semi arid	Arid
Plain	Low-land	Alluvial					1
		Ancient alluvial					2, 2a
		Deluvial-proluvial					3
		Aeolian					4, 4a
	High-land	Formation					5
Mountain	Foot-hills	Alluvial-proluvial				10, 10a	14, 14a
		Deluvial-proluvial					15
		Formation				11, 11a	
		Hum-mocky				12, 12a	
	Low-hill terrain	Tectonic-denuda-tion			8, 8a	13	
	Mid-moun-tains	Tectonic-denuda-tion		7	9		
	High-lands	Tectonic-denuda-tion	6				
Valley plain					16		
Erosion-denudation ledge					17		
Chemogenic (shor, salt marshes)					18		
Glaciers and rocks					19		

Fig. 2. Map of natural zones of Turkestan region; source: own study

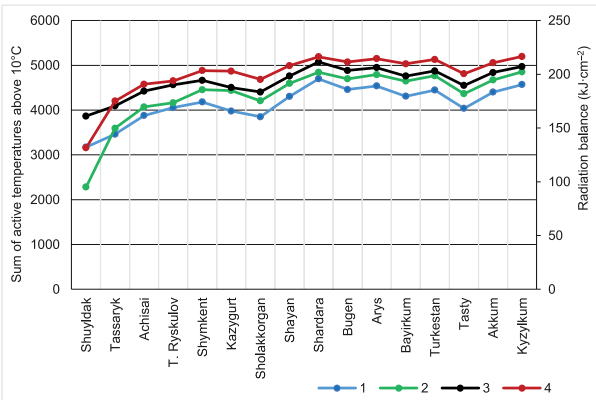


Fig. 3. Change of energy resources by weather stations of the Turkestan region; *1* = sum of biologically active temperatures above 10°C for 1941–1960, *2* = sum of biologically active temperatures above 10°C for 2001–2020, *3* = radiation balance (kJ·cm^{-2}) for 1941–1960, *4* = radiation balance (kJ·cm^{-2}) for 2001–2020; source: own study

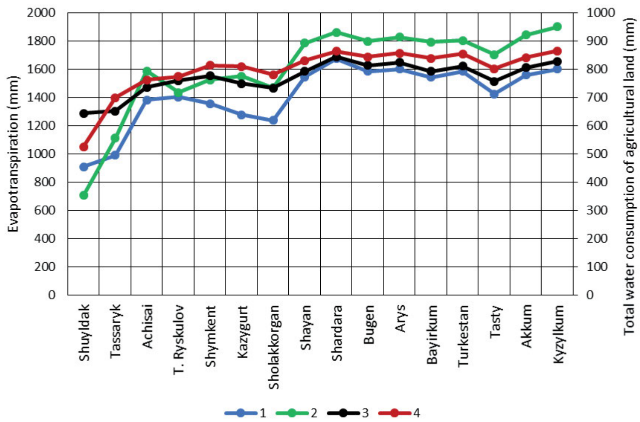
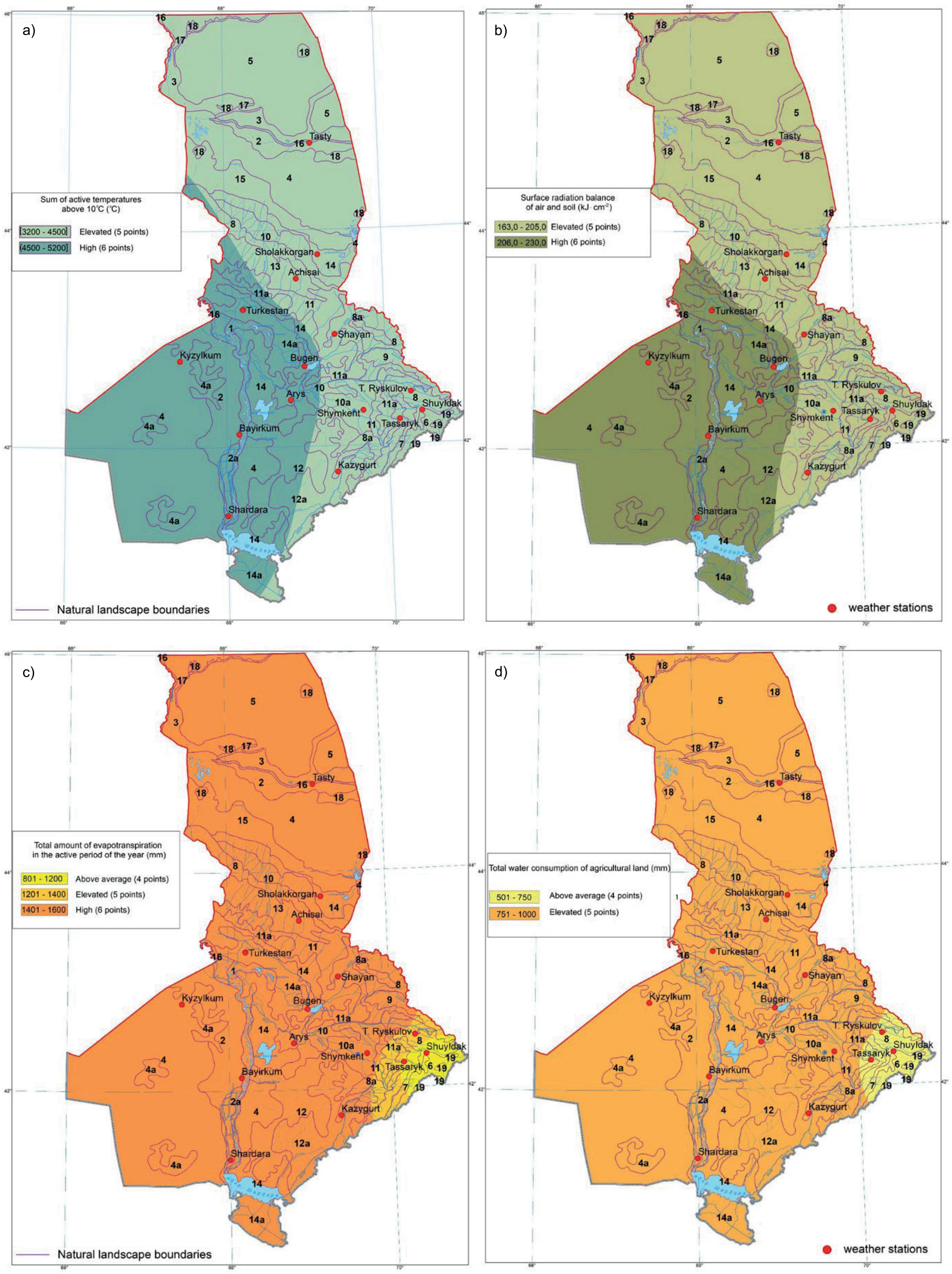


Fig. 4. Change of energy resources by weather stations of the Turkestan region; *1* = evaporation for 1941–1960, *2* = evaporation for 2001–2020, *3* = total water consumption of agricultural land for 1941–1960, *4* = total water consumption of agricultural land for 2001–2020; source: own study

according to the data obtained from Tasaryk weather station, an increase was observed: sum of biologically active air temperatures – from 3461.3 to 3594.0°C, photosynthetically active radiation – from 170.5 to 175.0 kJ·cm^{-2}, evapotranspiration from the water surface – from 993.0 to 1140.0 mm and water consumption of agricultural land (vegetation and soil cover) – from 682.0 to 700.0 mm, which indicates the increased energy resources (estimated at 5 points). At the same time, in the landscapes located in the vicinity of Shuyldak weather station, for the period under consideration, a decrease was observed: sum of biologically active air temperatures – from 2281.3 to 3172.2°C, photosynthetically active radiation – from 161.0 to 131.5 kJ·cm^{-2}, evapotranspiration from the water surface – from 911.0 to 707.0 mm and water consumption of agricultural land (vegetation and soil cover) – from 644.0 to 526.0 mm, which is associated with the high-altitude location and



Natural landscape boundaries

Class	Subclass	Sort	Type: Meadow alpine and subalpine	Forest-meadow-steppe	Steppe-dry-steppe	Semi arid	Arid
Plain	Low-land	Alluvial					1
		Ancient alluvial					2, 2a
		Deluvial-proluvial					3
		Aeolian					4, 4a
	High-land	Formation					5
Mountain	Foothills	Alluvial-proluvial				10, 10a	14, 14a
		Deluvial-proluvial					15
		Formation				11, 11a	
		Hummocky				12, 12a	
	Low-hill terrain	Tectonic-denudation			8, 8a	13	
	Mid-mountains	Tectonic-denudation		7	9		
	High-lands	Tectonic-denudation	6				
Valley plain			16				
Erosion-denudation ledge			17				
Chemogenic (shor, salt marshes)			18				
Glaciers and rocks			19				

Fig. 5. Maps of energy resources in the agricultural landscapes of Turkestan region: a) sum of biologically active temperatures ($\Sigma SBCT_i$ > 10°C), b) surface radiation balance of air and soil (kJ·cm^{-2}), c) total evapotranspiration in the biologically active period of the year (mm), d) total water consumption of agricultural land (mm); source: own study

availability of average to above average energy resources (estimated from 2 to 3 points).

- In the mountainous (low-hill and mid-mountain landscapes) area (Ashchysai and T. Ryskulov weather stations), covering parts of the territory administrative districts of Tyulkubas, Sauran regions and the urban agglomeration of Kentau, an increase was observed: sum of biologically active air temperatures – from 3877.3 to 4041.3°C, photosynthetically active radiation – from 184.3 to 193.8 kJ·cm^{-2}, evapotranspiration from the water surface – from 1385.0 to 1590.0 mm and water consumption of agricultural land (vegetation and soil cover) – from 737.0 to 775.0 mm and are estimated at 5 points.
- In the mountainous (foothill landscapes) semi-arid zone (Shymkent and Kazygurt weather stations), covering parts of the territories of the urban agglomeration of Shymkent and Kazygurt administrative district, an increase was observed: sum of biologically active air temperatures – from 3977.6 to 4454.2°C, photosynthetically active radiation – from 187.6 up 203.4 kJ·cm^{-2}, evapotranspiration from water surface – from 1280.0 to 1553.0 mm and water consumption of agricultural land (vegetation and soil cover) – from 750.0 to 814.0 mm, which indicates the increased energy resources (estimated at 5 points).
- In the arid mountainous (foothill landscapes) and plain (lowland and highland landscapes) areas, in the vicinity of Sholakkorgan, Tashkent, Shayan, and other weather stations, covering parts of the territories of Maktaaral, Zhetysay and other administrative districts, an increase was observed: sum of biologically active air temperatures – from 3849.0 to 5065.0°C, photosynthetically active radiation – from 183.4 to 223.8 kJ·cm^{-2}, evapotranspiration from water surface – from 1239.0 to 1828.0 mm and water consumption of agricultural land (vegetation and soil cover) – from 734.0 to 895.0 mm, which indicates the increased energy resources (estimated at 6 points).

Based on the calculations and modern GIS technologies, maps of energy resources in the agricultural landscapes of Turkestan region were constructed in terms of the sum of biologically active temperature above 10°C ($\Sigma SBCT_i$ > 10°C), radiation balance for biologically active period of the year (RB_i, kJ·cm^{-2}), TEB_i (mm) and ET_i (mm) (Fig. 4).

ASSESSMENT OF MOISTURE AND HEAT SUPPLY OF AGRICULTURAL LANDSCAPE USE

Based on integrated climate and energy indicators, including NMC_i, $\bar{R}_i$, HTC_i, BCP_i, HF_i, CL_i, impact of climate change on the natural moisture and heat supply of agricultural landscapes on a space-time scale was assessed using the data collected from 16 weather stations located in various natural zones of the Turkestan region.

Assessment of the natural moisture and heat supply for 1941–1960 showed that, in general, in the agricultural landscapes, there is a decreasing trend of moisture supply and an increase in heat supply (Fig. 6–8).

– In the mountainous area (highland, low-hill and foothill landscapes), according to Shuyldak and Tasaryk weather stations, a decrease was observed: natural moisture content – from 0.820 to 0.680, hydrothermal coefficient – from 2.36 to 2.10, bioclimatic potential – from 2.84 to 2.44, effective humidification index – from 116.5 to 114.1, climate favourable index – from 2.34 to 2.21 and only the radiation index of dryness increased

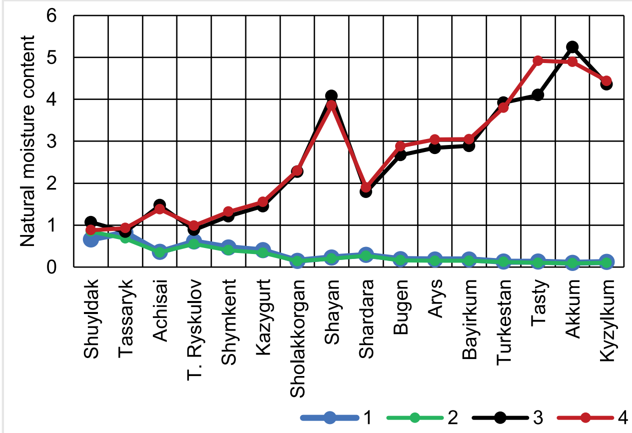


Fig. 6. Change of moisture and heat supply index by weather stations of Turkestan region; *1* = natural moisture content for 1941–1960 (–), *2* = natural moisture content for 2001–2020 (–), *3* = radiation index of dryness (heat availability) for 1941–1960 (–), *4* – radiation index of dryness (heat availability) for 2001–2020 (–); source: own study

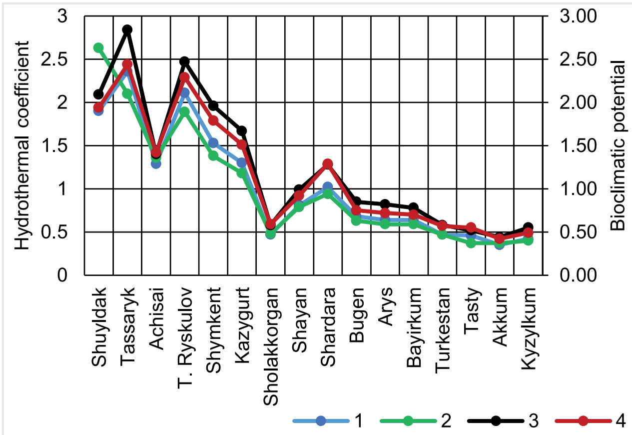


Fig. 7. Change of moisture supply index by weather stations of Turkestan region; *1* = hydrothermal coefficient for 1941–1960 (–), *2* = hydrothermal coefficient for 2001–2020 (–), *3* = bioclimatic potential for 1941–1960 (–), *4* = bioclimatic potential for 2001–2020 (–); source: own study

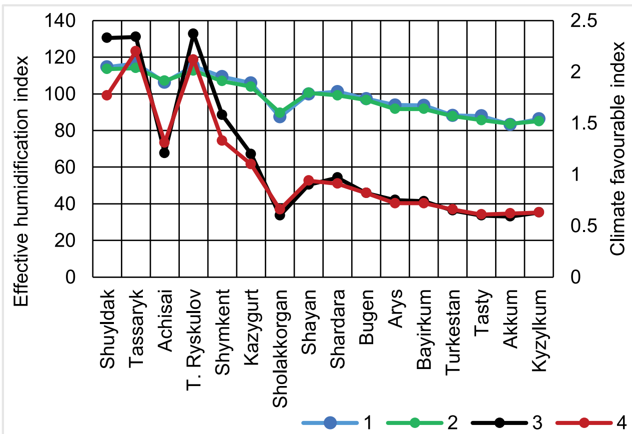


Fig. 8. Change of integrated climate index by weather stations of Turkestan region; *1* = effective humidification index for 1941–1960 (–), *2* = effective humidification index for 2001–2020 (–); *3* = climate favourable index for 1941–1960 (–), *4* = climate favourable index for 2001–2020 (–); source: own study

from 0.84 to 0.93, which indicates a decrease in the moisture content of the zone (estimated at 5 points).

– In the mountainous (low-hill and mid-mountain landscapes) area in the vicinity of Ashchysai and T. Ryskulov weather stations for 1941–2020, natural moisture content decreased from 0.36 to 0.35 and the radiation index of dryness – from 1.47 to 1.38. There is an increasing trend for the hydrothermal coefficient – an increase from 1.29 to 1.36, bioclimatic potential – from 1.40 to 1.42, effective humidification index – from 106.3 to 107.1, and the climate favourable index – from 1.21 to 1.31. According to these indicators, the landscapes of natural areas refer to the sub-arid and moderately insufficient humidification areas (estimated at 3–4 points).
– In the mountainous (foothill landscapes) semi-arid zone (Shymkent and Kazygurt weather stations) for 1941–2020, a decrease was observed: natural moisture content – from 0.47 to 0.34, hydrothermal coefficient – from 1.53 to 1.18, bioclimatic potential – from 1.67 to 1.51, effective humidification index – from 109.3 to 103.9, climate favourable index – from 1.58 to 1.33. The radiation index of dryness increased from 0.84 to 1.50. According to the estimated indicators, the landscapes of this area refer to arid or moderately insufficient moisture zones (estimated at 4 points).
– In the arid mountainous (foothill landscapes) and plain (lowland and highland landscapes) areas (according to Sholakkorgan, Tashkent, Shayan, Shardara, Bogen, Arys, Baiyrkum, Turkestan, Tasty, Kyzylkum and Akkum weather stations) for 1941–2020, a decrease was observed: natural moisture content – from 0.29 to 0.10, hydrothermal coefficient – from 1.02 to 0.37, bioclimatic potential – from 1.28 to 0.44, effective humidification index – from 101.2 to 85.6, climate favourable index – from 0.97 to 0.61, and only the radiation index of dryness increased from 1.79 to 4.92. In other words, during the period under consideration, in the landscapes of arid mountainous zones, a transition of the dryness index from dry to very dry was observed and is estimated at 1 point. In the landscapes of the arid plain zone, this indicator also changed from very insufficient moisture to extremely insufficient moisture (estimated at 1 point).

Thus, given a decrease in annual values of precipitation, which is the natural moisture supply of landscapes and determines their ecological productivity, an increase of the water shortage is currently observed in hydro-agrolandscapes.

ASSESSMENT OF CLIMATE ARIDITY OF AGRICULTURAL LANDSCAPE USE

Assessment of climate aridity is based mainly on the use of the two most important and well-studied factors – air temperature and amount of precipitation, where, based on them, IA_i, BIA_i and NIA_i are used as indicators (Fig. 9).

Assessment of climate aridity in the agricultural landscapes of the Turkestan region for 1941–2020 showed that, in general, there is an increasing trend of aridity from mountainous to arid plain landscapes.

– In the mountainous area (highland, low-hill and foothill landscapes) (location of Shuyldak and Tasaryk weather stations), the aridity index (aridity) decreased from 42.3 to 37.3, bioclimatic index of aridity – from 0.045 to 0.040, and only the normalised aridity index increased from 0.955 to 0.960.

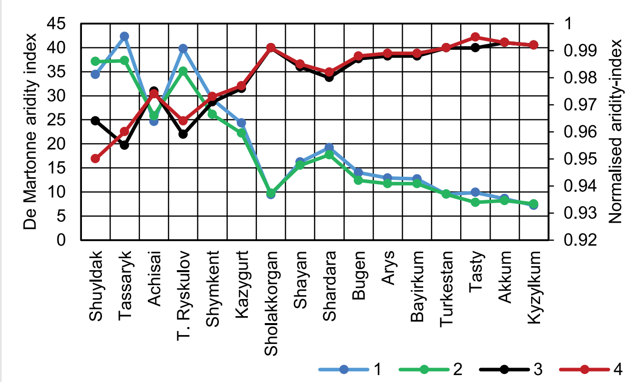


Fig. 9. Change of climate aridity in the agricultural landscapes of Turkestan region; *1* = De Martonne aridity index for 1941–1960 (–), *2* = De Martonne aridity index for 2001–2020 (–), *3* = normalised index of aridity for 1941–1960 (–), *4* = normalised index of aridity for 2001–2020 (–); source: own study

– In the mountainous (low-hill and mid-mountain landscapes) area, in the vicinity of Ashchysai weather station, the aridity index (aridity) increased from 24.6 to 25.8, bioclimatic index of aridity – from 0.025 to 0.026, while normalised index of aridity decreased from 0.975 to 0.974. In the area of T. Ryskulova weather station over the same period, the aridity index (aridity) decreased from 39.8 to 35.1, bioclimatic index of aridity – from 0.041 to 0.036, while the normalised aridity index increased from 0.959 to 0.964.
– In the mountainous (foothill landscapes) semi-arid zone (Shymkent and Kazygurt weather stations), aridity index (aridity) decreased, respectively, from 29.2 to 26.1 and from 24.3 to 22.2, bioclimatic index of aridity – from 0.029 to 0.027 and from 0.024 to 0.023, while the normalised aridity index increased from 0.971 to 0.973 and from 0.976 to 0.977.
– In the arid mountainous (foothill landscapes) and plain (lowland and highland landscapes) areas (Sholakkorgan, Tashkent, Shayan and other weather stations), in general, the integrated aridity index increased, especially in the vicinity of Kyzylkum weather station, located in the arid landscapes of the Aeolian plains.

Assessment of quantitative indicators of agroclimatic resources of agricultural landscapes in natural areas of the Turkestan region of the RK for 1941–2020 showed that the integrated indicators characterising natural energy resources and heat supply in all natural areas increase, and water supply decreases sharply, which entails an increase of aridity.

CONCLUSIONS

Assessment of the agroclimatic resources of agricultural landscapes in the natural areas of Turkestan region of the RK for 1941–2020 using long-term climatic indicators (average annual air temperature and annual precipitation) made it possible to establish that the following points.

1. Quantitative indicators of natural energy resources (heat supply) (according to the integrated indicators of the sums of biologically active air temperatures above 10°C and the radiation balance for biologically active period of the year, kJ·cm^{-2}) in the agricultural landscapes increased from 5 to 11%. An increase of this indicator is observed from mountainous to

plain arid landscapes, which drives an increase in the total evapotranspiration for the biologically active period of the year and the total water consumption of agricultural land for the biologically active period of the year.
2. Quantitative indicators of natural moisture content (according to the integrated indicators of the natural moisture component, the radiation index of dryness, hydrothermal coefficient, bioclimatic potential, effective humidification index and climate favourable index) in agricultural landscapes, in general, decreased from 4 to 10%. The decrease is observed from the mountains towards the plains of the arid zone, and clearly drives an increase in the deficit of total water consumption by 10–15%, which is a signal for the development of water security measures in the field of agricultural activity.
3. Quantitative indicators of the degree of aridity and continentality (according to the integrated aridity index, bioclimatic assessment of aridity and normalised aridity index) in the agricultural landscapes, increase from 5 to 10 % from the mountains towards the plains of the arid zone, that is, there is an increasing trend of aridity, which has a negative impact on the development of agricultural activities, requires a revision of the specialisation of agricultural units in the region.

ABBREVIATIONS

AAP_i = annual precipitation (mm)
$AAP_{i>10}$ = amount of precipitation for the period with average daily air temperatures above 10°C (mm)
AAT_i = average annual air temperature (°C)
AME_i = average monthly evapotranspiration (mm)
$AMRH_i$ = average monthly relative air humidity (%)
AMT_i = average monthly air temperature above 10°C (°C)
BIA_i = bioclimatic index of aridity (–)
BCP_i = relative value of bioclimatic potential (–)
CE_i = total evaporation for the year (mm)
CL_i = climate favourable index (–)
ESF_i = solar energy expenditure for the soil-forming process in natural zones (kJ·cm^{-2})
ET_i = total water consumption of agricultural land (mm)
HF_i = effective humidification index (–)
HTC_i = hydrothermal coefficient of G.T. Selyaninov (–)
IA_i = De Martonee aridity index (–)
L = latent heat of evaporation, numerically equal to 2.5 (kJ·cm^{-2})
MI_{di} = moisture index (–)
n = number of months where the average monthly air temperature is above 10°C
N_i = number of days in a month
NIA_i = normalised index of aridity (–)
NMC_i = natural moisture content (–)
$\bar{R}_i$ = "radiation index of dryness" or complex hydrothermal coefficient (–)
RK = Republic of Kazakhstan
RB_i = surface radiation balance of air and soil (kJ·cm^{-2})
TEB_i = total evapotranspiration in the biologically active period of the year (mm)
α = indicator of the complete use of radiation energy in soil-forming processes
$\Sigma AAHD_i$ = sum of air humidity deficit in the biologically active period of the year (100 Pa; 100 Pa = 1 mbar)

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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