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RESEARCH ARTICLE

Assessment of Natural Moisture Availability of Turkestan Region of the Republic of Kazakhstan

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Abstract. To increase the level of management efficiency in the agricultural sector of the economy, it is necessary to ensure the implementation of the sustainable environmental management principles, taking into account the spatial patterns of climate change and bioclimatic potential of the territory. The assessment of natural moisture availability of the natural areas of the Turkestan region of the Republic of Kazakhstan for 1941-2020 (by providing a comparative analysis of indicators for 1941-1960 and 2001-2020) was conducted based on the use of the natural moisture coefficient and hydrothermal index or "dryness index" predicated on energy resources (total of biologically active air temperatures above 10°C, photosynthetically active radiation, evaporating capacity and water consumption of agricultural land). The conducted survey has used the proven domestic, international and proprietary methods according to estimates of natural water availability in the natural areas. The results of a comparative analysis of climatic indices changes in the natural areas of the Turkestan region (by sixteen weather bureau stations) for 1941 to 2020 have shown that there is an increase in average annual air temperatures in all natural areas, and the annual precipitation tends downward which affects the formation of energy resources and natural water supply. The identified features of changes in the natural moisture coefficient and hydrothermal index or "dryness index" in natural area of Turkestan region, make it possible to adjust the spread of its boundaries and consider these changes in the territorial organization of agricultural nature management.

1. Introduction

Climate change is a global challenge of all mankind, which covers environmental, economic, and social aspects of sustainable development of the world's countries. Climatic changes are manifested in the intensity, frequency of climatic anomalies and extreme weather phenomena at different levels of the hierarchy in space and time (Pichura et al., 2022).

One of the main functions of climate is the support of soil and vegetation cover in the various natural areas distinguishing with quantitative values of average annual air temperature and annual atmospheric precipitation making impact on the provision of energy resources of natural systems and its moisture supply (Mustafayev and Ryabtsev, 2012; Kuderin et al., 2019). The moisture supply of the territories as a function of climatic indices depends primarily on the volume of annual precipitation and annual average air temperature which determines its relative instability on the space-time scales in different natural areas, and takes an important applied relevance as a basis of agricultural natural resource use (Huang et al., 2016, 2017).

Temperature increases, reduced precipitation and increased evaporation in Central Asia, documented in several studies (Xu et al., 2016; Yin et al., 2016; Patrick, 2017), increase the sensitivity of natural areas to droughts because of limited water resources, low-adaptive capacity and growing population. The climate changes in the territory of Kazakhstan, located in the northern part of Central Asia, have occurred somewhat faster in recent decades compared to other regions of the world situated in the same latitudinal zone (Zheleznova et al., 2022; Karatayev et al., 2022): the rate of change in average annual air temperatures over the past 20 years at all weather stations has increased from 0.8 to 2.2° C. Such changes can also impact erosion and salinization, the principal processes of desertification (Lal, 2012).

Under conditions of global climate change, forecasting of natural moisture availability and development trends of this process on a space-time scale in terms of natural zones and administrative units is used for leveling a negative impact of climatic indices on the territorial organization of agricultural natural management (Viana et al., 2022; Aldazhanova, 2022). Improving the prediction of natural moisture forecast in response to rainfall allows water resource managers to optimize irrigation schedules, plant water consumption and costs (Basak et al., 2022; Tursunova, 2022). In dry regions, soil water supply and soil temperature are key variables controlling agricultural productivity, and more favorable soil environments can greatly enhance crop yield, hereby improving food security (Wang et al., 2020; Yu et al., 2019).

The purpose of research is a study of changes in natural moisture availability in the natural areas of Turkestan region of the Republic of Kazakhstan for 1941-2020 (by providing comparative analysis of indicators within 1941-1960 and

2001-2020) using the natural moisture coefficient and hydrothermal index or "dryness index" based on the energy resources (total of biologically active air temperature above 10°C, photosynthetically active radiation, evaporativity and water consumption of agricultural land) in the conditions of climatic change.

2. Methods

Study Area

The research is concerned with the natural area of Turkestan region of the Republic of Kazakhstan. The region is located in the southern part of the Republic of Kazakhstan. The following natural zones are distinguished on the territory of the region with an area of 116 280 km^2 (4.3% of the territory of the Republic of Kazakhstan): forest-meadow-steppe zone of mid-mountains; steppe zone of low-hill terrain and midlands; semi-arid zone of foothills; arid zone of foothills, lowland and high land plains. All natural areas are characterized by a variety of natural and climatic conditions (Figure 1). The region's climate is sharply continental.

Figure 1. Map of natural areas of Turkestan region of the Republic of Kazakhstan

Data sources

The time series of the average annual temperature and annual precipitation indicators for 1941-2020 by sixteen weather stations represented in the following analytic databases: Kazgidromet RSE (Annual Bulletin, 2020), World Meteorological Organization (WMO) and in the "Weather and Climate" reference and information portal have been used as information support to assess the natural moisture availability of natural zones of the Turkestan region of the RK.

The initial information for the allocation of natural areas of the Turkestan region was: materials of the field landscape research of contributors, landscape map of the Republic of Kazakhstan.

An assessment of the homogeneity of climatic indicators (average annual air temperature and annual precipitation) in the territory of the Turkestan region on a spatio-temporal scale based on long-term data covering the period for 1941-2020 for 16 meteorological stations located in various natural zones using a linear trend was produced in the Microsoft program Excel , which showed that changes in climate indicators are statistically significant, confirming the heterogeneity of the time series (Zh. Mustafayev et al., 2023) .

Methods

The following indicators were used to assess the moisture availability of natural areas in the Turkestan region (Mustafayev and Ryabtsev, 2012): – natural moisture coefficient ($К_у$), enabling to assess the heat - and water availability of the territory which was determined according to the formula of N.N. Ivanov 1 :

$$К_у = О_с / Е_о, \quad (1)$$

where $О_с$ – precipitation amount, $Е_о$ – monthly average evaporation;

– hydrothermal index or "dryness index" ($\overline{R}_i$), representing the ratio of the radiation budget (Ri) to the heat input for evaporation of precipitation ($L \cdot О_{ci}$), which was determined by formula of M.I. Budyko 2:

$$\overline{R}_i = R_i / L \cdot O_{ci}, \quad (2)$$

where L – specific heat of evaporation assumed constant and equal to 2,5 kJ/cm^2, which, firstly, takes into account the idea of hydration (Dokuchaev, 1948) and the provision on the value of the ratio of the radiation balance to precipitation for the characterization of moisture conditions; secondly – qualifies the conditions of heat and moisture availability of soil and vegetation cover; thirdly – specifies considerably the conditions of formation of soil, hydrogeological and geochemical environment and, fourthly, it allows considering the nature and intensity of human anthropogenic activity.

The following estimation integral criteria have been used to assess changes in the energy resources indicators of climate in the natural areas of the Turkestan region for 1941-1960 and 2001-2020:

– sum of biologically active air temperatures ($\sum t_c, ^o C$) above 10°C, which was calculated by summing the product of average monthly air temperatures and the number of months with average monthly air temperatures above 10°C that was determined by formula 3 (Mustafayev and Ryabtsev, 2012):

$$\sum t_c, ^o C = \sum_{i=1}^{n} t_м \cdot N, \quad (3)$$

where $t_м$ – average monthly air temperature above 10 ° C; N – number of days in a month; n – number of months where the average monthly air temperature is above 10°C;

– photosynthetically active radiation (R_i, kJ/cm^2) during the biological active period of the year, which was determined according to the following modification of Yu. N. Nikolsky and V. V. Shabanova 4:

$$R_i = 4{,}1868 \cdot [13{,}39 + 0{,}0079 \cdot \sum t_i > 10^o C] \quad (4)$$

– monthly evaporation (E_o, мм), which was determined by formula of N.N. Ivanov 5:

$$E_o = 0{,}0018 (t_м + 25)^2 (100 - \alpha), \quad (5)$$

where $t_м$ – average monthly air temperature, ° C; t_α – average monthly relative humidity, %;

– water consumption by agricultural land (vegetation and soil cover) (ET_{ci}), which was determined by formula of M.I. Budyko 6:

$$\text{ET}_{ci} = 10 \cdot R_i \cdot L^{-1}, \quad (6)$$

where L – heat of evaporation numerically equal to 2,5 kJ/cm^3.

In the nature, annual photosynthetically active radiation (R_i) and precipitation ($О_{ci}$) qualify the material and energy environment enabling to determine the cost of solar energy for the soil formation process ($Q_{пi}$), which is determined by formula of V.R. Volobuev 7:

$$Q_{пi} = R_i \cdot exp(-\alpha \cdot \overline{R}_i), \quad (7)$$

where R_i – annual radiation balance of the soil surface (kJ/cm²); α – index of the complete use of radiant energy in soil-forming processes, numerically equal to 0,47; $\overline{R}_i$ – "radiation dryness index" or Nesterov's fire-danger index.

The favorable conditions for developing the soil formation process in the natural environment are observed in the natural and climatic conditions, where the Nesterov's fire-danger index ($\overline{R}$) is equal to 0,9-1,0, that commonly corresponds to the area of highly productive chernozem soil formation. By reference to specific features of these natural processes, potential cost of solar energy on the soil-forming process (Q_{ni}^{n}) with $\overline{R}_i = 1{,}0$ is determined by formula 8 (Mustafayev and Ryabtsev, 2012):

$$Q_{ni}^{n} = R_i \cdot exp(-\alpha), \tag{8}$$

In the natural environmental conditions, "excess solar energy on the soil-forming process" (ΔQ_{ni}^{u}), that is, the unused annual radiation balance of the soil surface (R_i) is determined by formula 9:

$$\Delta Q_{ni}^{u} = Q_{ni}^{n} - Q_{ni} = R_i \cdot exp(-\alpha) - R_i \cdot exp\left(-\alpha \cdot \overline{R}_i\right)$$
$$\Delta Q_{ni}^{u} = R_i\left[exp(-\alpha) - exp\left(-\alpha \cdot \overline{R}_i\right)\right] = R_i \cdot exp\left[-\left(\alpha - \alpha \cdot \overline{R}_i\right)\right];$$
$$\Delta Q_{ni}^{u} = R_i \cdot exp\left\{-\left[\alpha \cdot \left(1 - \overline{R}_i\right)\right]\right\} \tag{9}$$

The natural heat and moisture availability in the natural areas of the Turkestan region which has made it possible to establish the impact of climatic change on the natural moisture and heat supply of agricultural land (soil and vegetation cover) on the space-time scale is determined on the basis of the proposed integral climatic and energy indicators.

3. Results and Discussion

Average annual air temperatures and annual atmospheric precipitation of natural areas

A comparative analysis of data for the 1941-1960 and 2001-2020 periods for sixteen weather stations (Table 1) was conducted for identification of changes in annual average air temperature (t_i, °C) and annual atmospheric precipitation (O_{ci}, mm) affecting the natural moisture and heat supply of the natural areas of the Turkestan region.

A comparative analysis of changes in the average annual air temperature in the natural areas of the Turkestan region for the periods considered has showed that there is an increase in this indicator in all natural areas, except for the indicator at the Shuyldak weather station (forest-meadow steppe zone of midlands), where there was a decrease in the average annual air temperature by 1.3 ° C, which is due to the high-altitude location of this weather station with 1984 m elevation above sea level (Ugam mountain system).

It has been established that the rate of change in the average annual air temperature in the natural areas of the region over the past 20 years (2001-2020) has significantly increased from 0,8 (Tassaryk weather station, forest-meadow steppe zone of midlands) to 2,2° C (Tasty weather station, arid zone of low-land and high plains).

Table 1. Indicators of average annual air temperatures (t_i, ° C) and annual atmospheric precipitation (O_{ci}, mm) in the natural areas of the Turkestan region

Natural area	Weather stations	Climate indicators: Average annual air temperatures (t_i, ° C), on average for periods 1941-1960	2001-2020	difference	Annual atmospheric precipitation (O_{ci}, mm), on average for periods 1941-1960	2001-2020	difference
1. Forest-meadow steppe zone of mid-mountains	1. Shuyldak	7.5	6.2	-1.3	602.0	601.0	-0.1
	2. Tassaryk	9.3	10.2	0.8	816.0	754.0	-62.0
2. Steppe zone of low-hill terrain and midlands	3. Achisai	10.3	11.4	1.1	500.0	552.0	52.0
	4. T. Ryskulov	11.5	12.4	0.9	855.0	786.0	-69.0
3. Semi-arid zone of foothills	5. Shymkent	11.9	13.6	1.7	640.0	615.0	-25.0
	6. Kazygurt	11.3	13.6	1.3	517.0	524.0	7.0
4. Arid zone of foothills, lowland and high plains	7. Shayan	11.6	13.3	1.7	349.0	362.0	13.0
	8. Sholakkorgan	9.1	11.0	1.9	180.0	203.0	23.0
	9.Shardara	12.6	14.8	2.2	230.0	230.0	0.0
	10. Bugen	11.8	13.7	1.9	305.0	294.0	-11.0
	11. Arys	12.5	14.1	1.6	290.0	282.0	-8.0
	12. Bayirkum	11.7	13.6	1.9	275.0	275.0	0.0
	13. Turkestan	11.8	13.8	2.0	207.0	225.0	18.0
	14. Tasty	8.7	10.9	2.2	185.0	163.0	-22.0
	15. Akkum	11.3	13.1	1.8	154.0	174.0	20.0
	16. Kyzylkum	12.1	13.8	1.7	190.0	195.0	5.0

Source: Annual Bulletin of monitoring the state and climate change in Kazakhstan (2020). Astana: The national hydrometeorological service of the Republic of Kazakhstan

From the above calculation data (Table 1), a decrease in the amount of annual atmospheric precipitation in all natural areas has been established, specifically in the forest-meadow steppe zone of mid-mountains (Tassyryk weather station) by 62,0 mm, in the steppe zone of low-hill terrain and midlands (T. Ryskulov weather station) by 69,0 mm, in the semi-arid zone of the foothills (Shymkent weather station) by 25,0 mm, in the arid zone of foothills, lowland and high plains (weather stations – Bugen, Arys and Tasty) from 11 to 22 mm. It was noted that the general trend of changes in the amount of precipitation in all natural zones of the Turkestan region in recent years (2001-2020) is directed downwards.

The conducted analysis of changes in climatic indices in the natural areas of the Turkestan region in the space-time terms has allowed establishing increase in the average annual air temperature, especially during 2001-2020, which had an effect on the natural moisture availability of natural areas decreasingly since the increase of air temperature has caused expectable decreases in the annual average values of relative humidity enhancing the evaporative capacity of the natural environment.

This is also confirmed by data indicating in general an increase in average annual air temperatures and a decrease in annual precipitation in all five countries of Central Asia (Borisova, 2013), in the mountainous regions of Central Asia (Zholdosheva et al., 2017), watershed areas of the transboundary Ile River located in the Xinjiang Uygur Autonomous Region (XUAR) of the People's Republic of China and the Republic of Kazakhstan (Zh. Mustafayev and L.M. Ryskulbekova, 2022) and the Shu river basin, formed from the Terskey - Alatoo glaciers and the Kyrgyz Range on the territory of the Kyrgyz Republic and the maganization zone, where the sands of Moiynkum of the Republic of Kazakhstan are located (Zh. Mustafaev et al., 2019).

Energy resources of the climate of natural areas

The conducted assessment of changes in energy resources indicators based on climatic indices (Table 1) depending on the average annual air temperature and solar radiation in the natural areas of the Turkestan region for 1941-1960 and 2001-2020 has demonstrated that (Table 2):

Table 2. Indicators of energy resources of natural areas climate of the Turkestan region

Natural area	Weather stations	Periods	Indicators of energy resources climate			
			($\sum t_c, ^oC$)	R_i, kJ/cm ²	E_{oi}, mm	ET_{ci}, mm
1. Forest-meadow-steppe zone of mid-mountains	1. Shuyldak	1941-1960	3172.2	161.0	911.0	644.0
		2001-2020	2281.3	131.5	707.0	526.0
		difference	-890.9	-29.5	-204	-118
	2. Tassaryk	1941-1960	3461.3	170.5	993.0	682.0
		2001-2020	3594.9	175.0	1114.0	700.0
		difference	133.6	4.5	121	18
2. Steppe zone of low-hill terrain and midlands	3. Achisai	1941-1960	3877.3	184.3	1385.0	737.0
		2001-2020	4069.3	190.7	1590.0	763.0
		difference	192	6.4	205	26
	4. T. Ryskulov	1941-1960	4054.0	190.2	1405.0	761.0
		2001-2020	4163.8	193.8	1438.0	775.0
		difference	109.8	3.6	33	14
3. Semi-arid zone of foothills	5. Shymkent	1941-1960	4179.5	194.3	1359.0	777.0
		2001-2020	4454.2	203.4	1526.0	814.0
		difference	274.7	9.1	167	37
	6. Kazygurt	1941-1960	3977.6	187.6	1280.0	750.0
		2001-2020	4435.8	202.8	1553.0	811.0
		difference	458.2	15.2	273	61
4. Arid zone of foothills, lowland and high plains	7. Sholakkor-gan	1941-1960	3849.4	183.4	1239.0	734.0
		2001-2020	4206.3	195.2	1472.0	781.0
		difference	356.9	11.8	233	47
	8. Shayan	1941-1960	4301.9	198.3	1547.0	793.0
		2001-2020	4594.9	208.0	1788.0	832.0
		difference	293	9.7	241	39
	9. Shardara	1941-1960	4695.6	211.4	1677.0	845.0
		2001-2020	4842.6	216.2	1863.0	865.0
		difference	147	4.8	186	20
	10. Bugen	1941-1960	4458.0	203.5	1586.0	814.0
		2001-2020	4695.7	211.4	1799.0	845.0

Natural area	Weather stations	Periods	Indicators of energy resources climate			
			($\sum t_c, ^o C$)	R_i, kJ/cm ^{2}	E_{oi}, mm	ET_{ci}, mm
		difference	237.7	7.9	213	31
	11. Arys	1941-1960	4537.4	206.1	1603.0	825.0
		2001-2020	4790.6	214.5	1828.0	858.0
		difference	253.2	8.4	225	33
	12. Bayirkum	1941-1960	4307.7	198.5	1544.0	794.0
		2001-2020	4646.5	209.7	1794.0	839.0
		difference	338.8	11.2	250	45
	13. Turkestan	1941-1960	4445.4	203.1	1588.0	812.0
		2001-2020	4765.8	213.7	1805.0	855.0
		difference	320.4	10.6	217	43
	14. Tasty	1941-1960	4035.5	189.5	1426.0	758.0
		2001-2020	4365.3	200.4	1705.0	802.0
		difference	329.8	10.9	279	44
	15. Akkum	1941-1960	4399.5	201.6	1560.0	806.0
		2001-2020	4671.3	210.6	1846.0	842.0
		difference	271.8	9	286	36
	16. Kyzylkum	1941-1960	4567.6	207.1	1603.0	829.0
		2001-2020	4851.6	216.5	1903.0	866.0
		difference	284.0	9.4	300.0	37

Source: Annual Bulletin of monitoring the state and climate change in Kazakhstan (2020). Astana: The national hydrometeorological service of the Republic of Kazakhstan

– in the forest-meadow steppe zone of mid-mountains (Shuyldak weather station) during the period under consideration there were decreases in: sum of biologically active air temperature values ($\sum t, ^o C$) by 890,9° C; photosynthetically active radiation (R_i) by 29,5 kJ/cm²; evaporation from the water surface (E_{oi}) by 204,0 mm and water consumption by agricultural land (vegetation and soil cover) (ET_{ci}) by 118,0 mm which is due to the high-altitude location of the natural area (1984 m above sea level). According to data of the Tassaryk weather station located in this natural area, but well below in the mountains (1523 m above sea level) there is already an increase in: sum of biologically active air temperatures by 133,6°C, photosynthetically active radiation by 4,5 kJ/cm², evaporation from the water surface by 121,0 mm and water consumption by agricultural land (vegetation and soil cover) by 18,0 mm;

– in the steppe zone of low-hill terrain and midlands (T. Ryskulov and Achisai weather stations), there has been an increase in: sum of biologically active air temperatures from 109,8 to 192,0° C, photosynthetically active radiation from 3,6 to 6,4 kJ/cm², evaporation from the water surface from 33 to 205 mm and water consumption by agricultural land from 14 to 26 mm;

– in the semi-arid zone of foothills, (Shymkent and Kazygurt weather stations), there was an increase in: sum of biologically active air temperatures from 274,7 to 458,2° C, photosynthetically active radiation from 9,1 to 15,2 kJ/cm², evaporation from the water surface from 167,0 to 273,0 mm and water consumption by agricultural land from 37,0 to 61,0 mm.

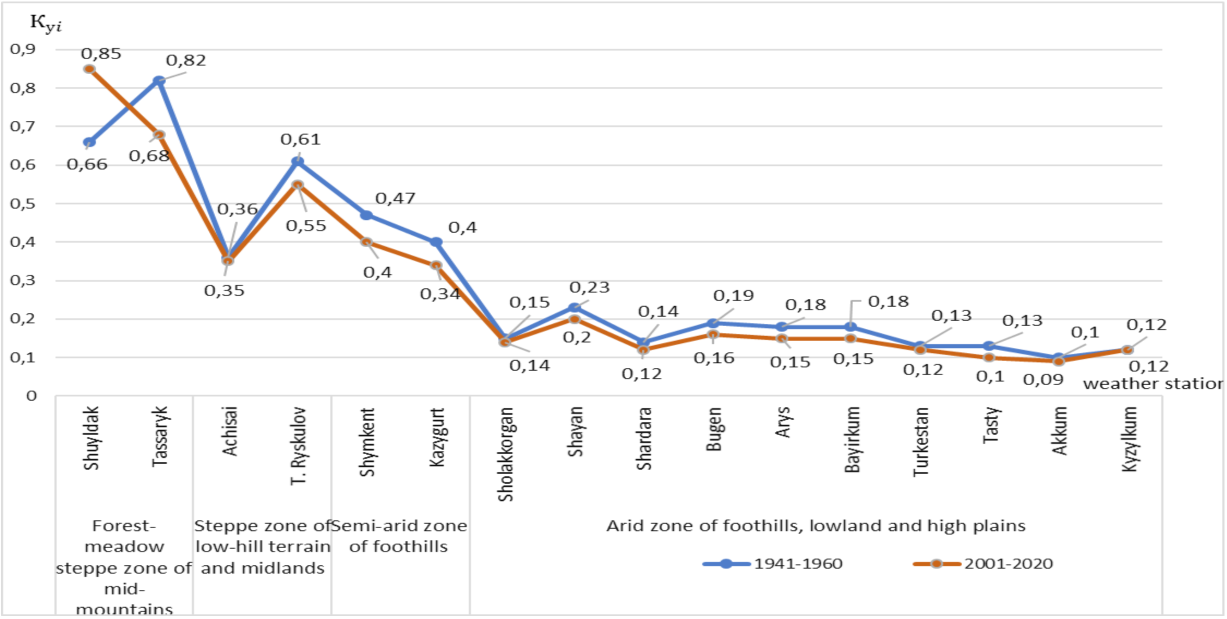
– in the arid zone of foothills, lowland and high plains (Sholakkorgan, Shayan, Shardara, Bugen, Arys, Bayirkum, Turkestan, Tasty, Kyzylkum and Akkum weather stations), there was an increase in: sum of biologically active air temperatures from 147,0 to 356,9° C, photosynthetically active radiation from 4,8 to 11,8 kJ/cm², evaporation from the water surface from 186,0 to 300,0 mm and water consumption by agricultural land from 20,0 to 47,0 mm.

Therefore, in the natural areas of the Turkestan region there is a positive trend of changes in the average annual air temperature and negative trend in the amount of annual precipitation which will have an impact on the productivity of agricultural land. In particular, there will be increase in the sum of biologically active air temperature values and photosynthetically active radiation since as energy resources of the climate which will drive up the evaporation from the water surface and water consumption by agricultural land (vegetation and soil cover).

Natural moisture and heat supply of natural areas

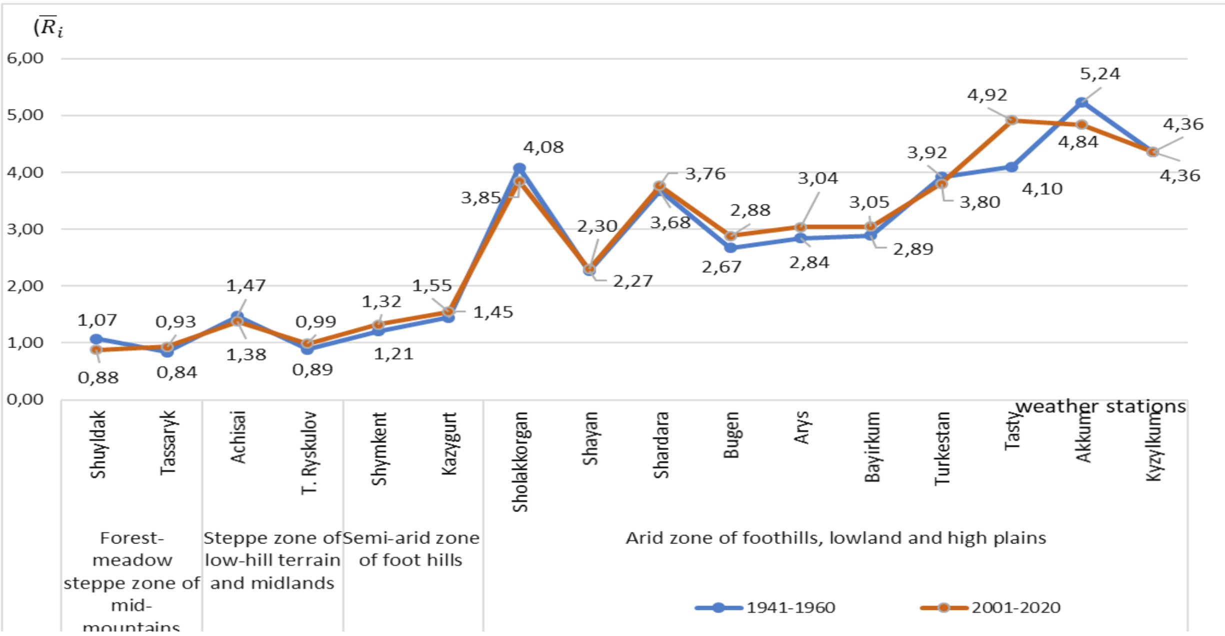
A comparative assessment of changes in natural moisture and heat supply in the natural areas of the Turkestan region in 1941-1960 and 2001-2020 on the basis of climatic indices (Table 1) has showed that generally in all natural areas there is a downward trend in the water availability indicator (natural moisture K_{yi}) and increase in the heat supply indicator (Nesterov's fire-danger index or dryness index – $\overline{R}_i$) (Figure 2-3).

Comparison of changes in indicators of moisture and heat supply of the territory of the Turkestan region during two periods - 1941-1960 and 2001-2020 shows that the coefficient of natural moisture in the forest-meadow-steppe zone of the middle mountains decreased by 0.14, in the steppe zone of the low mountains and middle mountains by 0.06, in the semi-desert zone of the foothills by 0.07 and in the desert zone of the foothills, low and elevated plains by 0.03. At the same



Source: Annual Bulletin of monitoring the state and climate change in Kazakhstan, 2020

Figure 2. Change in the coefficient of natural moisture (K_{yi}) in the natural areas of the Turkestan region for the periods 1941-1960 and 2001-2020



Source: Annual Bulletin of monitoring the state and climate change in Kazakhstan, 2020

Figure 3. Changes in the hydrothermal index (dryness index-$\overline{R}_i$) in the natural areas of the Turkestan region for the periods 1941-1960 and 2001-2020

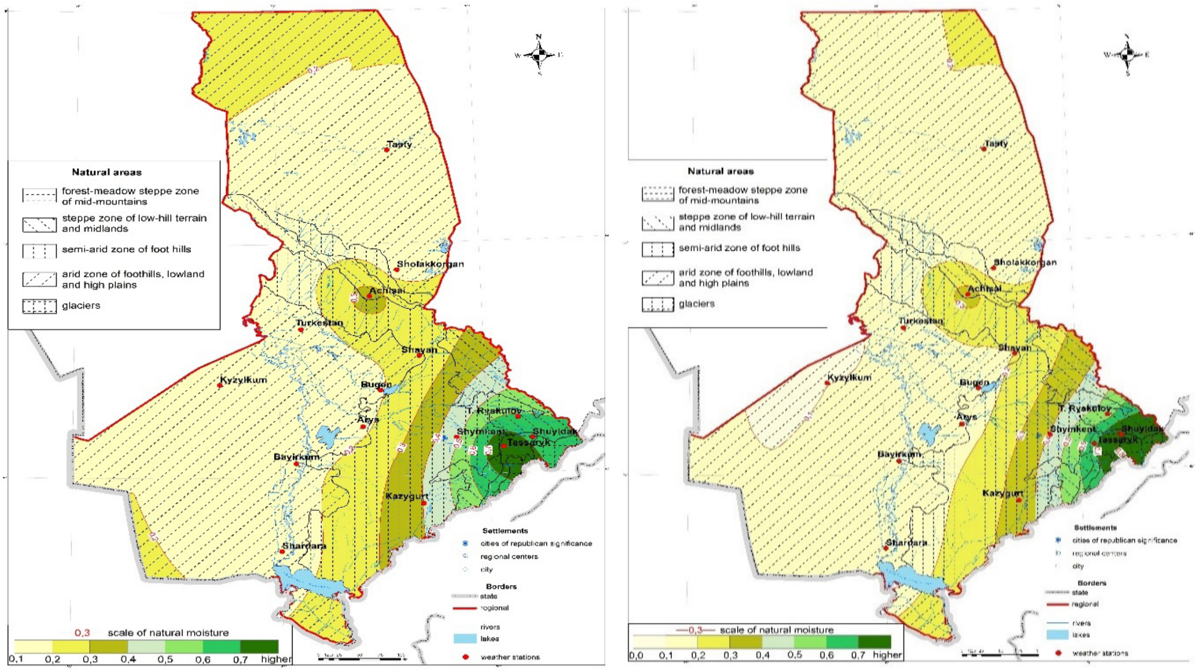
time, the complex hydrothermal indicator or "dryness index" characterizing the heat supply in the forest-meadow-steppe zone of the middle mountains increased by 0.14, in the steppe zone of the low mountains and middle mountains by 0.10, in the semi-desert zone of the foothills by 0.11 and in the desert foothill zone, low and high plains by 0.21, which can enhance the processes of plant species turnover and biodiversity loss in all natural zones of the Turkestan region.

The obtained scenario forecasts of changes in the climatic moisture and heat supply of landscapes for agricultural use in the Turkestan region on a spatio-temporal scale as a whole, to some extent, are consistent with the results of studies aimed at studying the moisture supply of the territory of the river basins Rhine, Tagus, Ganges, Lena, V. Huanghe, W. Yangtze, Niger, Mackenzie, W. Mississippi, W. Amazon and Darling located in different regions of the globe (Gusev et al., 2021) and agricultural lands of the Almaty and Zhetysu regions of the Republic of Kazakhstan (Mustafaev Zh., 2022), which showed that changes in the variability of annual values of moisture supply with possible climate change are directly proportional to annual precipitation and inversely proportional to average annual air temperatures, characterizing the evaporative capacity of the natural system.

Generally, in the space-time terms, in the natural areas of the Turkestan region from 1941 to 2020 there is a decrease in the coefficient of natural moisture by 15-20%, with simultaneous increase in the Nesterov's fire-danger index (dryness index), which affects the spatial spread of the boundaries of natural areas, and requires the development of measures to ensure water security in agricultural activities, with respect to the natural and climatic differences of the Turkestan region.

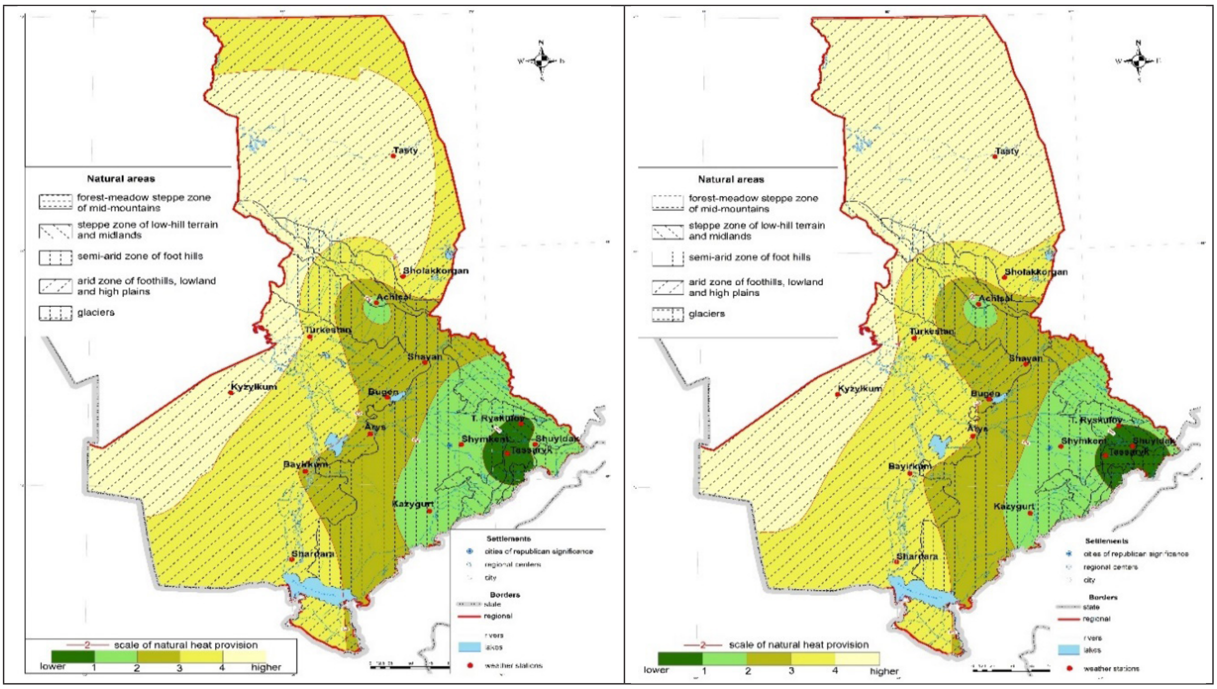
The identified spatial variations in the boundaries of natural moisture and hydrothermal index in the natural areas of the Turkestan region for 1941-1960 and 2001-2020 are shown in Figure 4-5, that have an impact on energy cost for the soil formation.

The natural ($Q_{\pi i}$) and potential ($Q^{n}_{\pi i}$) cost of solar energy on the soil-forming process under the same conditions of the radiation balance of the soil surface (R_i) is highly correlated to the Nesterov's fire-danger index (dryness index) ($\overline{R}_i$), which is reported in our estimated calculations for the periods from 1941-1960 to 2001-2020 within the boundaries of the natural areas of the Turkestan region:



a) for 1941-1960 years average b) for 2001-2020 years average

Figure 4. Spatial variations of natural moisture boundaries in the natural areas of the Turkestan region



a) for 1941-1960 years average b) for 2001-2020 years average

Figure 5. Spatial variations in the boundaries of natural heat provision in the natural areas of the Turkestan region

In general, the background characteristics of the conditions of the radiation balance of the soil cover (t_i,°C) and annual precipitation (O_{ci})) and, consequently, the natural (Q_{ni}) and potential (Q_{ni}^{n}) solar energy costs calculated from them for the soil-forming process of soils in landscapes of agricultural use in the Turkestan region, strictly speaking, reflect average annual air temperature and annual precipitation under possible climate change. At the same time, the potential cost of solar energy for the soil-forming process (Q_{ni}^{n}) from the forest-meadow-steppe zone of the middle mountains to the desert zone of the foothills, low and high plains increases from 115.2 kJ/cm ^{2} to 135.2 kJ/cm ^{2}, the natural costs of solar energy soil-forming process (Q_{ni}) decreases from 92.2 kJ/cm ^{2} to 26.9 kJ/cm ^{2} and the unused ("excess") annual radiation balance of the soil cover (ΔQ_{ni}^{u}) increases from 23.0 kJ/cm ^{2} to 108.0 kJ /cm ^{2}, which may have led to the formation of low-productive soil and vegetation cover of landscapes for agricultural use in the Turkestan region.

At the same time, it should be noted that in all natural zones of the Turkestan region, as a result of climate change, the shortage of water demand for agricultural land and the cost of solar energy for the soil formation process will increase, which are one of the most climate-dependent natural processes that determine the ecological, food and water security of the region. All this requires more detailed research in the field of assessing the agro-resource potential of landscapes for agricultural use, clarifying the current boundaries of natural and climatic regions, and revising the agro-climatic zoning scheme, taking into account the cost of solar energy for the soil-forming process, since such forecasts are practically absent at present.

4. Conclusions

Scenario forecasts of changes in average annual air temperatures and annual precipitation and, consequently, the sum of biologically active air temperatures, radiation balance of soil cover and evapotranspiration in the biologically active period of the year, water consumption of agricultural land, solar energy consumption for soil formation, climatic moisture and heat supply in different natural zones in different natural conditions of the Turkestan region showed that, in comparison with the periods of 1941-1960, in the period for 2001-2020, the energy resources of the landscape for agricultural use increase by 10-15%, and their natural moisture supply decreases by 5-10 %, which served to increase the shortage of water demand for agricultural land by 15-20%.

Current trends in climate change, due to an increase in the average annual air temperature and a decrease in annual precipitation and the associated decrease in the natural moisture supply of landscapes for agricultural use in the Turkestan region, will entail serious consequences for the territorial organization of agricultural production, which requires the development and implementation of measures to adaptation to climate change.

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