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RESEARCH ARTICLE

Dynamics of the bioclimatic potential of agroecological zones of the Altai Territory in the conditions of modern climatic and anthropogenic changes

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Abstract

The steppe zone is characterized by high dynamism of environmental conditions including sharp climatic fluctuations that affect both the possibilities of agriculture and the state of steppe landscapes. Further development of agriculture without taking into account changing climatic and environmental factors increases risks both for steppe ecosystems and for the sustainability of agriculture. The field production of the agro-climatic zones of the Altai Territory is characterized by the high variability of gross yields associated with the dynamics of precipitation, air temperature, and soil fertility. Under the current conditions, the analysis of the temporal and spatial dynamics of bioclimatic potential is of high practical importance for the development and implementation of adaptive agricultural technologies. A retrospective analysis was carried out and a modern bio-climatic characteristic of model territories representing various agroecological zones was compiled for this purpose. The object of research was data on average daily, average monthly, and average annual air temperatures, the level of precipitation, the water vapor pressure, and relative humidity. Statistical processing of analytical data was carried out in Excel. Calculations revealed significant temporal and spatial dynamics of the BCP. Spatially, it is characterized by a significant decrease in a north-western orientation. The lowest average values, 1.71-1.81 units, were observed in the Kulunda and Rubtsovskaya agroecological zones, with a coefficient of variation of more than 20.0%. The Zarinskaya and Aleyskaya agroecological zones were characterized by the highest values of BCP, and the Predgornaya zone presented maximum values of BCP, at the level of 2.70 units with high stability. Temporally, the BCP of the Zarinskaya, Kulunda, and Priobskaya agroclimatic zones is characterized by a negative trend; in other zones, its almost zero balance is noted. A sufficiently expressed difference in the BCP of various agroecological zones has an impact on the realization of the biological potential of cultivated crops. Analysis of the level of development of the vegetative mass of spring wheat by determining NDVI confirmed this assumption. For a systematic assessment of the influence of climatic and anthropogenic factors on the production process of field crops and the development of measures for the rational use of agricultural landscapes, it is advisable to determine the potential yield according to the BCP, determine the degree of its implementation in the economic harvest and justify techniques for leveling limiting factors in agrotechnology of individual agroecological zones.

Keywords
Altai Territory, Kulunda, ecology, ecological factor, agroecological zones, bioclimatic potential, phytomass, vegetation indices, adaptive agrotechnologies

Introduction

The agricultural lands of Western Siberia are characterized by significant variability in the gross harvest of crops, which forms high risks to the food security of the population (EMISS State Statistics 2022).

Thus, in the Omsk region, with an average gross harvest of grain and leguminous crops of 2938.3 thousand tons, its variability was 20.2% for 2000-2021 with fluctuations from 1689.6 thousand tons in 2012 to 4002.5 thousand tons in 2009. The Novosibirsk region during this period was characterized by even greater instability of gross yields, varying from 1240.1 thousand tons in 2012 to 3403.9 thousand tons in 2001, with a coefficient of variation of 22.0%. Altai Territory with the highest average grain harvest of 4237.6 thousand tons also distinguished by high temporal variability from the regions mentioned above, although against their background, it was characterized by a slightly lower coefficient of variability of gross yields, amounting to 19.6%.

A similar pattern should be noted concerning the instability of grain production of the main grain food crop – spring wheat.

As the analysis of literature sources shows, crop variability in the steppe zone of Russia is more associated with changes in the amount of precipitation, the dynamics of air temperature (Weather and climate 2022; Precipitation and air temperature 2022), and anthropogenic factors accompanied by variations in yields and harvesting areas (Vasilyev et al. 2020; Kincharov et al. 2020). It follows that in conditions of extreme depletion of the soils on the territories of traditional farming in the methodological basis of agricultural technologies, consideration of climatic and soil factors should be given an important place.

The works of Russian scientists widely present the results of research to identify the relationship of productivity of field crops with natural factors (Kiryushin 1993, 2000; Koshelev and Petsevich 2015; Sokolova and Belyayev 2017).

It should be noted that similar studies are being conducted in various parts of the world affected by anthropogenic degradation of soil cover and climate change. In particular, the results of research by scientists from China (Guo et al. 2022; Wang et al. 2022), Kazakhstan (Karatayev et al. 2022; Schierhorn et al. 2020), Germany (Sielingand Kage 2022), Argentina (Arisnabarreta and Miralles 2015) and many other countries are widely presented in the press.

There is a conviction that the modern period in the history of the Earth's climate is characterized by a steady increase in aridity associated with a significant rise in thermal resources with a decreasing amount of precipitation (Pavlova and Karachenkova 2020).

Such dynamics of meteorological parameters are observed almost everywhere and are accompanied by the intensification of scientific research aimed at adapting various sectors of the national economy and, above all agriculture, to them (Siptits 2018; Antonov 2018).

A retrospective analysis of actively practiced agrotechnologies with aggressive tillage showed that intensive mechanical impact on the soil while plowing, numerous cultivations, harrowing, and other technological techniques accompanied by a violation of the soil structure leads to the formation of clumpy or dusty fractions, and reduces its moisture capacity, water permeability and water retention capacity (Perfileva and Korolyova 2015). In addition, enhanced mineralization of organic matter occurs; degradation risks as various erosive phenomena increase (Chernova et al. 2020; Khripunov et al. 2021).

As a result of such a technological approach, the vast territories of cultivated lands of the steppe zone in Russia, as the main food granary of the country, are today characterized by very low soil fertility. Researchers point to a 25-75% decrease in organic matter content in them compared with natural analogs (Rusanov 2022).

Deterioration of soil yield properties in combination with climate change is accompanied by instability of agriculture and forms food, financial and social risks.

In this regard, the identification of natural and anthropogenic factors limiting the high realization of the biological potential of field crops and destabilizing grain production is highly relevant for the development of agrotechnologies adapted to agroecological conditions aimed at their optimization.

As is known, the compliance of the territory of crop cultivation with their agroecological requirements is largely determined by the resources of heat and moisture. They are expressed in the form of the average annual air temperature, the sum of active, more than 10°C temperatures, the amount of annual precipitation, and the amount of precipitation of the active temperature period.

The availability of these resources during the growing season characterizes the hydrothermal conditions of the territory and in domestic science is most often expressed as the hydrothermal coefficient of G.T.Selyaninov or HTC (Selyaninov 1928).

The rapid decline in soil fertility with the soil-intensive orientation of agricultural technologies, mainly focused on the irrevocable exploitation of natural resources, especially in the worked-out fields that are characteristic of the post-virgin regions of Russia, often acts as no less a deterrent to the high realization of the biological potential of cultivated crops than the conditions of heat and moisture supply.

In this regard, simultaneously with the analysis of hydrothermal conditions of agricultural lands, it is advisable to carry out their assessment by bioclimatic potential. The calculation of its value and the assessment of the completeness of use are also of high importance in the development and improvement of zonal resource-saving farming systems.

The tasks implemented in the study concerning data collection and analysis of the temporal and spatial dynamics of hydrothermal conditions and the bioclimatic potential of agroecological zones of the Altai Territory are extremely relevant, and the obtained results are of high practical importance.

The purpose of the research was to study the resources of heat and moisture availability of agricultural lands in the Altai Territory, to analyze their dynamics over thirty years from 1990 to 2020, to compile a modern hydrothermal characteristic according to the HTC of the Selyaninov, and to analyze the dynamics of the bioclimatic potential of model territories.

Material and methods

Altai Territory, located in the flat and foothill part of the greater Altai, is a unique region with a variety of natural conditions, where almost all natural zones of the northern hemisphere meet. Such a variety of agroecological conditions, taking into account the modern needs of agricultural production in more efficient use of natural resources and conservation of biological diversity of steppe farmlands, determined the need to divide the region into agroecological zones (Tatarintsev et al. 2016). They are allocated according to the soil and environmental conditions of crop formation of strategic crops cultivated everywhere, primarily grain crops.

Based on quantitative indicators of soil bonification and field crop yields, V.A. Rassypnov (Rassypnov 2012) proposed a grouping of administrative districts of the Altai Territory by agroecological zones, which we accepted as a priority (Table1).

In the direction of the development and implementation of innovative technologies in the steppe land use of the Altai Territory, we conducted a collection and retrospective analysis of hydrothermal conditions according to the hydrothermal coefficient of G.T. Selyaninov in the context of individual agroecological zones representing relatively homogeneous territories suitable for the implementation of common technological approaches (Rassypnov 2012). Also, we estimated model agricultural territories by bioclimatic potential or BCP (Shashko 1985; Tikhonov 2000).

Table 1. Grouping of administrative districts of the Altai Territory by agroecological zones, according to V.A. Rassypnov (Rassypnov 2012)

Agroecological zone	Brief landscape and soil-climatic characteristics	Administrative districts
Kulunda	Dry steppe on chestnut soils of the Kulunda lowland	German National, Slavgorod, Tabunsky, Kulundinsky, Klyuchevsky, Mikhailovsky, Uglovsky
Rubtsovskaya	Arid steppe on the chernozems of the southern Priobsky plateau	Burlinsky, Khabarovsky, Suetsky, Blagoveshchensky, Zavyalovsky, Rodinsky, Romanovsky, Volchikhinsky, Yegoryevsky, Rubtsovsky, Rubtsovsk
Priobskaya	Forest outlier steppe on ordinary chernozems of the Priobsky plateau	Pankrushikhinsky, Krutikhinsky, Bayevsky, Kamensky, Tyumentsevsky, Shelabolikhinsky, Mamontovsky, Rebrikhinsky, Pavlovsky
Aleyskaya	Moderately arid steppe on ordinary chernozems of the Priobsky plateau	Kalmansky, Topchikhinsky, Aleysky, Ust-Pristansky, Shipunovsky, Novichikhinsky, Pospelikhinsky
Biyskaya	Forest-steppe on leached chernozems and gray forest soils of the Bie-Chumysh upland plain	Talmensky, Barnaul, Pervomaisky, Koshikhinsky, Troitskiy, Zonal, Biysk, Biysky
Zarinskaya	Deciduous forests and settled meadows on the leached chernozems of the Bie-Chumysh upland plain and the black soils of the podzolized and dark gray forest soils of the Salair Foothills	Zalesovsky, Zarinsky, Zarinsk, Kytmanovsky, Togulsky, Yeltsovsky, Tselinny, Saltonsky
Predgornaya	Meadow steppe on the chernozems of the Pre-Altai plain	Bystroistoksky, Smolensky, Sovetsky, Krasnogorsk, Belokurikha, Altai, Petropavlovsk, Ust-Kalmansky, Soloneshensky, Krasnoshchekovsky, Charyshsky, Kurinsky, Zmeinogorsky, Loktevsky, Tretyakovsky

The object of the research was information on average daily, average monthly, and average annual air temperatures, the level of precipitation, the water vapor pressure, and relative humidity recorded by seven meteorological stations dedicated to various agroecological zones of the Altai Territory. The source of meteorological data was the freely available specialized arrays for climate research of the All-Russian Research Institute of Hydrometeorological Information – the World Data Center (RRIHI-WDC) (Precipitation and air temperature 2022) and other electronic resources (Weather and climate 2022). Seven municipalities (administrative districts) of various agroecological zones of the Altai Territory have been accepted as model territories – Slavgorod (Kulundinskaya), Rodinsky (Rubtsovskaya), Kamensky (Priobskaya), Aleysky (Aleyskaya), Pervomaisky (Biysk), Tselinny (Zarinskaya) and Zmeinogorsky (Predgornaya).

To analyze the hydrothermal conditions of the Kulunda agroecological zone, data from the weather stations Slavgorod, Rubtsovskaya – Rodino, Priobskaya – Kamen-on-Obi, Aleyskaya – Aleysk, Biyskaya – Barnaul, Zarinskaya – Tselinnoye, Predgornaya –Zmeinogorsk, located in the municipalities of the same name, were used.

Characteristics of agroecological zones according to the HTC were carried out in accordance with the accepted classification. At values of HTC from 1.3 to 1.6, humidification conditions were characterized as humid, from 1.0 to 1.3 – as slightly arid, from 0.7 to 1.0 – as arid, from 0.4 to 0.7 – as very arid and below 0.4 – as dry (Agrometeorology).

The bioclimatic potential of the model territories (BCP) was calculated by the formula (Shashko 1985):

$$BCP = C_{g(ch)} \cdot \sum t > 10°C \ / \ 1000°C, \qquad (1)$$

where: BCP – relative value of bioclimatic potential; $C_{g\ (ch)}$ – the growth coefficient according to the annual indicator of atmospheric humidification; $\sum t > 10°C$ – the sum of active, more 10 °C average daily air temperatures, °C.

The physical meaning of the bioclimatic potential lies in the fact that the productivity of agricultural crops (Zhukov et al.1989) at the achieved level of agricultural technology is determined by the availability of nutrients to plants associated with the presence of moisture in the soil on the one hand and the thermal regime that determines the speed of biochemical reactions during photosynthesis and the intensity of microbiological processes in the soil on the other hand. In this regard, the bioclimatic potential also reflects the degree of availability to culture plants of nutrients contained in the soil solution in a particular territory (Gulyanov 2010).

The formula (Shashko 1985) was used to calculate the growth coefficient according to the annual indicator of atmospheric humidification (Cg (ch)), which expresses the ratio of yield with the available moisture supply to its maximum possible value with optimal moisture supply:

$$C_{g(\text{ку})} = \lg (20\ CH), \qquad (2)$$

where: CH – the coefficient of annual atmospheric humidification.

The coefficient of annual atmospheric humidification (CH) was determined by dividing the annual amount of precipitation by the sum of the average daily air humidity deficits:

$$CH = \sum P / (\sum d), \qquad (3)$$

where: $\sum P$ – annual precipitation, mm; $\sum d$ – the sum of the average daily air humidity deficits, hPa.

The normalized difference vegetation index of crops was determined based on publicly available satellite images of Landsat 8 and Santienel, with a spatial resolution of 15-30 m/pixel, posted on online resources OneSoil.ai and Sentinel-hub.com. The obtained data were applied to the cartographic basis in the NextGIS software package with subsequent processing in Arc Map.

Statistical processing of analytical data was carried out in Excel.

The analysis of heat supply resources revealed their noticeable spatial variability. Thus, the average annual air temperature for 1990-2020 in the context of agroecological zones varied from 3.3 °C in the Rubtsovskaya and Aleyskaya agroecological zones to 2.1 °C in the Priobskaya (Table 2).

Against the background of heat supply, the moisture resources of agroecological zones were characterized by greater spatial and temporal variability. Its peculiarity has become a widespread decrease in the amount of precipitation during the active temperature period and a decrease in the annual amount of precipitation, with the exception of only the Priobsky and Predgornaya zones (Table 3).

Table 2. Heat supply resources of agroecological zones of the Altai Territory, 1990-2020

Agroecological zone	Weather station	Average annual air temperature			The sum of active temperatures		
		Average, °C	Coefficient of variation, %	Trend, C°	Average, °C	Coefficient of variation, %	Trend, C°
Kulunda	Slavgorod	3.0	31.7	0.3	2810	7.2	130
Rubtsovskaya	Rodino	3.3	29.5	0.2	2753	6.5	160
Priobskaya	Kamen-on-Obi	2.1	47.0	0.1	2539	6.3	100
Aleyskaya	Aleysk	3.3	29.5	0.3	2715	6.2	120
Biyskaya	Barnaul	2.8	34.1	0.3	2587	6.3	130
Zarinskaya	Tselinnoe	2.6	36.3	-0.1	2464	6.1	70
Predgornaya	Zmeinogorsk	3.4	29.1	0.0	2590	6.1	90

Table 3. Moisture resources of agroecological zones of the Altai Territory, 1990-2020

Agroecological zone	Weather station	Annual precipitation			Precipitation for the period of active temperatures		
		Average, mm	Coefficient of variation, %	Trend, mm	Average, mm	Coefficient of variation, %	Trend, mm
Kulunda	Slavgorod	310	23.6	-23	195	31.9	-37
Rubtsovskaya	Rodino	326	21.3	-27	211	27.0	-29
Priobskaya	Kamen-on-Obi	345	21.0	19	224	27.6	-13

Agroecological zone	Weather station	Annual precipitation			Precipitation for the period of active temperatures		
		Average, mm	Coefficient of variation, %	Trend, mm	Average, mm	Coefficient of variation, %	Trend, mm
Aleyskaya	Aleysk	464	25.1	-14	271	32.3	-31
Biyskaya	Barnaul	443	15.0	-14	271	19.1	-50
Zarinskaya	Tselinnoe	514	25.7	-159	318	26.1	-102
Predgornaya	Zmeinogorsk	705	17.3	98	364	21.3	-27

The analysis of hydrothermal conditions of the growing season revealed their significant spatial variation in the context of various agroecological zones, convincingly illustrated by Selyaninov's HTC (Table 4).

The general trend of the dynamics of hydrothermal conditions, characteristic of all agroecological zones without exception, was the negative trend of the HTC, amounting to 0.11-0.28 units and most expressed in the Biyskaya and Zarinskaya zones.

The calculation and analysis of the BCP in addition to the analysis of the HTC allowed us to obtain a more objective picture of the dynamics of environmental factors that determine the productivity of agrocenoses at the implemented level of agricultural technology.

Calculations revealed significant temporal and spatial dynamics of the BCP in model territories represented in all agroecological zones (Table 5).

Table 4. Hydrothermal characteristics of agroecological zones of the Altai Territory, 1990-2020

Agroecological zone	Weather station	Selyaninov's HTC		
		Average, mm	Coefficient of variation, %	Trend, C°
Kulunda	Slavgorod	0.71	36.1	-0.17
Rubtsovskaya	Rodino	0.77	30.0	-0.15
Priobskaya	Kamen-on-Obi	0.90	31.7	-0.11
Aleyskaya	Aleysk	1.01	31.7	-0.11
Biyskaya	Barnaul	1.06	23.0	-0.26
Zarinskaya	Tselinnoe	1.33	27.8	-0.28
Predgornaya	Zmeinogorsk	1.42	24.3	-0.16

Table 5. Bioclimatic potential of agroecological zones of the Altai Territory, 1990-2020

Agroecological zone	Weather station	The sum of average daily air humidity deficits, hPa	The coefficient of annual atmospheric humidification	Growth coefficient for annual atmospheric humidification	Bioclimatic potential of the territory (BCP)	
					Average	Trend
Kulunda	Slavgorod	1458	0.22	0.62	1.71	-0.19
Rubtsovskaya	Rodino	1417	0.24	0.66	1.81	-0.05
Priobskaya	Kamen-on-Obi	1207	0.30	0.75	1.88	-0.05
Aleyskaya	Aleysk	1205	0.39	0.87	2.36	0.09
Biyskaya	Barnaul	1240	0.36	0.85	2.19	0.09
Zarinskaya	Tselinnoe	1179	0.44	0.93	2.28	-0.31
Predgornaya	Zmeinogorsk	1243	0.57	1.05	2.70	-0.00

The lowest average absolute values of the BCP of the analyzed period among all agroecological zones of the Altai Territory were noted in the dry steppe on chestnut soils of the Kulunda lowland and the arid steppe on the chernozems of the southern Priobsky plateau. So, in the Slavgorod model territory, the BCP of the thirty years was 1.71. Here, its highest temporal variability was also observed – from 0.98 in 2012 to 2.22 in 2016, with a coefficient of variation of 21.1%.

The highest values of the BCP were characterized by the Zarinskaya, Aleyskaya, and Predgornaya agroecological zones located in the zones of deciduous forests and meadows on the leached chernozems of the Biya-Chumysh upland plain, in the moderately arid steppe on the ordinary chernozems of the Priobsky plateau and the black soils of the podzolic and dark gray forest soils of the Salair Foothills and meadow steppes on the chernozems of the Pre-Altai plain. So, in the Zmeinogorsk model territory, the average BCP turned out to be 2.70 with the smallest variation over the years, amounting to 8.4%.

The Priobskaya and Biyskaya agroecological zones, confined to the forest outlier steppe on the ordinary chernozems of the Priobskaya plateau and the forest-steppe on the leached and gray soils of the Biya-Chumysh upland plain, were characterized by average values of BCP at the level of 1.88-2.19 units.

Results

The analysis of experimental data showed that the greatest temporal variability of the average annual air temperature, with a coefficient of variation of 47.0%, was noted in the Priobskaya agroecological zone. In Kulunda, Biyskaya, and Zarinskaya agroecological zones, its variability was at 15.3-12.9-10.7 percentage points below and by another 2.2-4.6-7.2 percentage points below – in the Kulunda, Aleyskaya, and Predgornaya zones.

In the Kulunda, Rubtsovskaya, Priobskaya, Aleyskaya, and Biyskaya agroecological zones, there is a tendency to increase the average annual air temperature, amounting to 0.1-0.3 °C or 4.7-10.7%, in the Predgornaya zone its zero balance was noted, and in the Zarinskaya zone a negative trend was revealed at 0.1 °C or 3.8%.

The consequence of the noted spatial variations in the temperature regime of the air in the studied thirty years was a sufficiently expressed variation in the amounts of active temperatures. The greatest thermal resources of the period with an average daily air temperature above 10 °C, exceeding 2800 °C, with the highest coefficient of variation of 7.2%, were noted in the Kulunda agroecological zone. In other territories, they were 57-346 °C lower, with minimum values of 2464 °C in the Zarinskaya agroecological zone.

Thermal resources of the studied territories in comparison with the average annual air temperature were characterized by relatively low temporal variability, amounting to 6.1-7.2%. At the same time, their low positive trend was also noted, from 70 °C or 2.8% in Zarinskaya to 160 °C or 5.8% in Rubtsovskaya agroecological zones.

With the maximum annual precipitation of 705 mm in the Predgornaya zone and the minimum value of 310 mm in the Kulunda, the difference was 395 mm or 127%. With a sufficiently high temporal variability of atmospheric humidification, characteristic of all the studied zones, the lowest variability at the level of 15.0% was noted in Biyskya, and the highest, 10.7 percentage points higher, in Zarinskya agroecological zones. The highest negative trend of annual precipitation, exceeding the 30.0% level, was also noted in the Zarinskaya zone. On the contrary, the Predgornaya agroecological zone in the study period was characterized by a positive trend in annual precipitation, amounting to 98.0 mm or 13.9%.

During the period of active temperatures, similar spatial dynamics of atmospheric humidification were observed, although the contrast between the studied regions was less pronounced. The difference between the maximum 364 mm in the Predgornaya zone and the minimum 195 mm in the Kulunda zone was 169 mm or 86.6%. At the same time, it should be noted that the peculiarity of atmospheric humidification in the warm period of the year was its higher variability, which exceeded the same indicator in annual terms by 0.4 percentage points in the Zarinskaya zone, and 8.3 percentage points in the Kulunda zone.

The negative trend of atmospheric precipitation during the active temperature period, which is most pronounced in Zarinskaya - 102 mm or 32.1%, Biyskaya - 50 mm or 18.4%, and Kulunda - 37 mm or 18.9% agroecological zones, is also noteworthy.

In accordance with the accepted classification, the humidification conditions in the Kulunda agroecological zone, on average for 1990-2020, turned out to be the most limited, described values of the HTC, characteristic of arid and very arid zones. The driest year was 2010 with an HTC of 0.29, and the wettest in 1992 with an HTC of 1.16. It should be emphasized that in three years from thirty, 1997, 2010, and 2012, or in 9.7% of the years, the humidification conditions here were generally characterized as dry with an HTC below 0.4 and in fourteen or 45.1% of the years as very dry, with HTC 0.7-0.4. A distinctive feature of the climate in this zone was the recurrence of very arid conditions for several years in a row, observed, for example, from 2004 to 2008 or from 2019 to 2021.

Humidification conditions close to the described ones also developed in the Rubtsovskaya agroecological zone, with an average HTC of the analyzed period of 0.77, with the only difference that dry conditions were noted here only in one year or 3.2% of years, and very dry conditions – in eight years or 25.8%. Periods with very arid humidification conditions turned out to be less prolonged – no more than two years in a row.

In the Priobskaya agroecological zone, a more favorable hydrothermal regime was noted, generally characterized as arid with an HTC of 0.9, but with a fairly high proportion of years with slightly arid, at the level of 22.5% and humid (9.3%) conditions.

The Aleyskaya and Biyskaya agroecological zones were characterized by slightly arid humidification conditions, with an HTC of 1.01-1.06. There were no dry years with an HTC below 0.4 and only 3 in the Aleyskaya zone and 2 in the Biyskaya zone of very dry years, while five or 16.1% of years in the Aleyskaya zone were observed up to six or 19.3% of the years in the Biyskaya zone are wet.

The most favorable hydrothermal regime was observed in the Zarinskaya and Predgornaya agroecological zones, characterized as wet, with an HTC of 1.33-1.42. There was not a single dry and very dry year, and the share of dry years was only 12.9% in the Zarinskaya zone and 9.6% in the Predgornaya zone. At the same time, 29.0% of years with an HTC of 1.69 – 2.04 exceeding the upper limit characteristic of the wet zone were noted. Moreover, such years were repeated several years in a row, such as 1993-1995, 2013-2014, and 2016-2018.

Practical interest is the direction of the change in the BCP (trend) reflecting the dynamics of climatic factors and soil fertility, which form the basis of agrotechnical measures of an adaptive nature (Fig. 1).

It should be emphasized that there is no uniformity in the changes in the BCP of various agroecological zones during the analyzed period.

Thus, in the Kulunda agroecological zone, with the lowest average values of BCP, its noticeable negative trend was revealed – by 0.19 units or 11.1%, which indicates an even greater decrease in the favorability of environmental factors for the high realization of the biological potential of field crops. The Predgornaya agroecological zone, with the lowest variation of the BCP over the years, was characterized by its zero trends, indicating the relative stability of external conditions. The situation is quite stable according to the BCP in the Aleiskaya and Biyskaya agroecological zones, where there was even a certain tendency of its growth - by 0.09 units or 3.8%.

A significant decrease in the bioclimatic potential in one of the most humid agroecological zones – Zarinskaya, which amounted to 13.6% over the analyzed period, should be highlighted.

On the whole, summing up the retrospective analysis of the bioclimatic potential, agroecological zones of the Altai Territory in descending order of the BCP can be arranged in the following order: Predgornaya, Aleyskaya, Zarinskaya, Biyskaya, Priobskaya, Rubtsovskaya, and Kulundinskaya.

Correlation analysis of time series of factors determining the bioclimatic potential of the studied territories allowed us to identify certain dependencies, both inherent in the entire area of the Altai Territory and characterized by spatial features (Table 6).

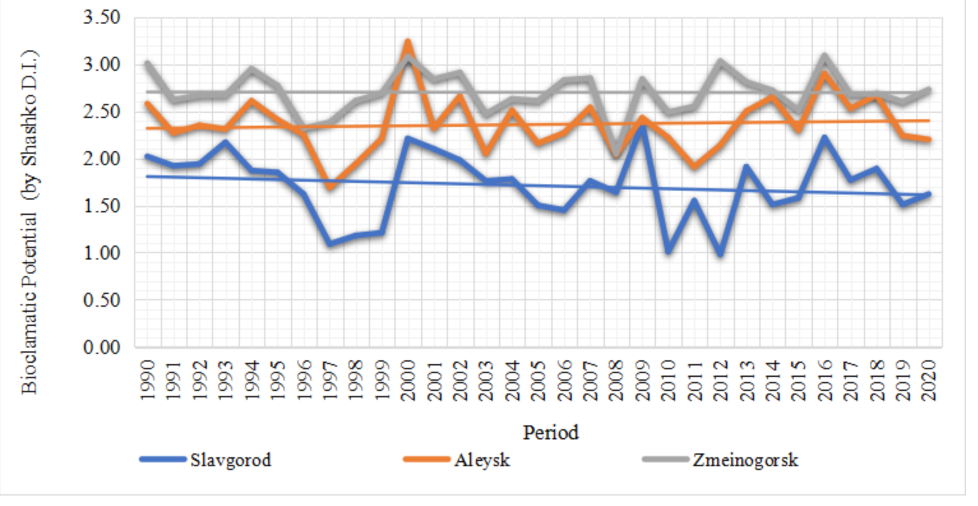

Figure 1. Spatial and temporal dynamics of the bioclimatic potential of model territories of various agroecological zones in the Altai Territory, 1990-2020.

Table 6. The relationship of bioclimatic potential with its defining parameters in various agroecological zones of the Altai Territory, 1990-2020

Agroecological zone	Weather station	Correlation of the BCP with its defining parameters, correlation coefficient (r)				
		The sum of active (more than 10 °C) temperatures of the growing season, °C	Annual precipitation, mm	The sum of average daily air humidity deficits, hPa	The coefficient of annual atmospheric humidification	Growth coefficient
Kulunda	Slavgorod	-0.45	0.96	-0.69	0.91	0.96
Rubtsovskaya	Rodino	-0.18	0.88	-0.68	0.94	0.94
Priobskaya	Kamen-on-Obi	-0.36	0.94	-0.65	0.89	0.93
Aleyskaya	Aleysk	-0.29	0.93	-0.46	0.94	0.93
Biyskaya	Barnaul	-0.13	0.86	-0.51	0.81	0.83

Agroecological zone	Weather station	Correlation of the BCP with its defining parameters, correlation coefficient (r)				
		The sum of active (more than 10 °C) temperatures of the growing season, °C	Annual precipitation, mm	The sum of average daily air humidity deficits, hPa	The coefficient of annual atmospheric humidification	Growth coefficient
Zarinskaya	Tselinnoe	-0.08	0.93	-0.38	0.91	0.91
Predgornaya	Zmeinogorsk	-0.02	0.84	-0.37	0.26	0.81

Thus, the direct relationship of the BCP with the annual amount of atmospheric precipitation, the coefficient of annual atmospheric humidification, and the growth coefficient in terms of annual atmospheric humidification are common to all agroecological zones. The relationship is reversed with the sum of the active temperatures of the growing season and the sum of the average daily air humidity deficits.

The degree of intensity of direct relation according to the parameters defining the BCP is strong in all agroecological zones, and certain features are noted concerning feedback.

The most pronounced average feedback of the BCP with the sum of the active temperatures of the growing season was observed in the Kulunda agroecological zone, r = -0.45. In the Priobskaya zone, it decreased by 0.09 units and by another 0.07 units in the Aleyskaya zone. In other territories, the relationship is weak, with a correlation coefficient from 0.18 to 0.02; the least expressed relationship is noted in the Zarinskaya and Predgornaya agroecological zones. In order of decreasing the strength of the connection, the studied zones are arranged in the following sequence – Kulundinskaya, Priobskaya, Aleyskaya, Rubtsovskaya, Biyskaya, Zarinskaya, and Predgornaya.

A similar pattern was noted for the sum of air humidity deficits, only the relationship of this parameter with the BCP is reversed and more pronounced than the sum of the active temperatures of the growing season. In the context of individual agroecological zones, it has a similar character, but there are also features. The similarity of the relationship lies in its greater intensity, close to strong with a correlation coefficient of 0.69, in the Kulunda agroecological zone and less pronounced, weak, with a correlation coefficient of 0.37, in the Predgornaya zone. A feature is a slightly different order of agroecological zones as the strength of the connection decreases – Kulundinskaya, Rubtsovskaya, Priobskaya, Biyskaya, Aleyskaya, Zarinskaya, Predgornaya.

Summing up the analysis of the magnitude and dynamics of the bioclimatic potential in the context of individual agroecological zones of the Altai Territory, it should be emphasized its significant spatial and temporal variability. In spatial terms, it is characterized by a significant decrease, having a north-western orientation, and in time - a decrease, most characteristic of the Kulunda, Rubtsovskaya, Priobskaya, and especially Zarinskaya zones.

It is obvious that the difference in the favorability of the external conditions of various agroecological zones, which is sufficiently expressed according to the BCP, has a significant impact on the realization of the biological potential of the cultivated crops and the yield.

The analysis of the level of development of the vegetative mass of field crops, as evidence of the favorable climate for the realization of their biological potential, using the normalized difference vegetation index or NDVI confirmed this assumption.

The determination of NDVI agrocenoses of spring wheat, which has a high correlation with the phytometric parameters of crops and the yield of the economically valuable part of the crop (Gulyanov 2019) in various agroecological zones, revealed its significant spatial variability and quite obvious connection with the BCP.

Thus, in the Slavgorod model territory, with the lowest level of BCP among the agroecological zones of the Altai Territory, during the maximum development of the vegetative mass of spring wheat, the average value of NDVI was equal to 0.45 units with a range of variation of 0.23 units – from 0.32 to 0.55 for the growing season. Crops were distinguished by a significant diversity of phytometric parameters, the coefficient of variation NDVI in various elementary areas of the surveyed fields exceeded 12.0% (Fig. 2a).

In the Zmeinogorsk model territory, with the BCP exceeding the same indicator of the Slavgorod model territory by 1.57 times, the NDVI of wheat fields was 1.67 times higher, with average values of 0.75 units and a range of variation from 0.69 to 0.80. The crops were characterized by lower phytomass heterogeneity with a spatial variation coefficient of NDVI not exceeding 3.0% (Fig. 2b).

Figure 2. Spatial variation and variability of NDVI in agrocenoses of spring wheat of model territories of various agroecological zones in the Altai Territory, 2022.

Conclusion

Following the above, for a systematic assessment of the impact of modern climatic and anthropogenic changes on the production process of crops and the development of measures for the rational use of agricultural landscapes, it is advisable to determine the potential yield of field crops according to the BCP, compare it with the economic yield, determine the degree of implementation of the BCP and identify limiting factors for each agroecological zone. Their results are extremely relevant for the development and implementation of the most appropriate technologies for agricultural land use, taking into account climatic and anthropogenic trends and aimed at preserving, restoring, and effectively using the landscape and biological diversity of steppe farmlands.

The established decrease in BCP has not yet resulted in a proportional decrease in yield. On the contrary, the development of technologies and the general culture of agriculture in the Altai Territory contributed to the fact that the yield showed a steady upward trend, actually doubling compared to 1970-1980 from 1.0 to 1.8-2.0 t/ha in recent years.

It has been established that the decline of the BCP over the past 30 years, judging by the preserved areas of the Stipa capillata steppes of Kulunda and the southern part of the Priobsky plateau, has not had a noticeable impact on steppe phytocenoses. At the same time, there is, especially in Kulunda, overgrowing of little-used hayfields and pastures, mainly in the vicinity of villages, in floodplains, and on the first terraces of rivers, primarily with narrow-leaved oleaster (*Elaeágnus angustifólia*). At the edges of ribbon forests, common pine (*Pinus sylvestris*) and sea-buckthorn (*Hippophae rhamnoides*) are rapidly advancing on untilled areas, creating an original oleaster-pine-sea buckthorn-stipa capillata savannoid specific to the Kununda of the first quarter of the XXI century. There is also a rapid advance of American maple (*Acer negundo*) and small-leaved elm (*Ulmus parvifolia*) from forest belts to crops of perennial grasses and even to the edges of fields. Concerning forest belts, we can talk about the expansion of the American maple, which replaces the falling tree and shrub species.

For woody and shrubby vegetation, the reduction of BCP is not essential, but the reduction of pasture load has proved to be fundamental, up to complete removal in many places. In these conditions, woody and shrubby vegetation is actively introduced mainly to old fallows, crops of perennial grasses, and even to the fields of the main commercial crops.

In general, it is impossible to recognize unambiguously negative the formation of oleasters, as well as pine-sea buckthorn- oleaster savannoids. Of course, they reduce the potential quality of farmland, primarily as hayfields, making it difficult to re-involve an area in arable land, but create an original landscape that diversifies the steppe one, with economic, environmental, environmental, and scientific potential perhaps not disclosed yet. This potential can be revealed concerning medicinal raw materials, primarily sea buckthorn and related species, refugiums of hunting species, and lands for beekeeping.

The conducted studies have confirmed the underutilization of the bioclimatic potential in the virgin and post-virgin areas of the Altai Territory at the end of the XX century. The subsequent development of technologies and the general culture of agriculture of all forms of ownership have created a trend of steady growth in actual yields in conditions of decreasing bioclimatic potential. That is, the active development of the underutilized reserve at the end of the XX century continues, even with its downward trend. At the same time, especially in the eastern part of the Altai Territory, technologies already allow us not only to reach the possibilities of bioclimatic potential but even to surpass it.

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References

Antonov SA (2018) Analysis of the dynamics of the climatically determined amount of black fallow in the Stavropol Krai. Science News in APC 1 (10): 5–8. https://doi.org/10.25930/2218-855x-1-10–511

Arisnabarreta S, Miralles D (2015) Grain number determination under contrasting radiation and nitrogen conditions in 2-row and 6-row barleys. Crop and Pasture Science 66 (5): 456–465. https://doi.org/10.1071/CP14208

Chernova OV, Alyabina IO, Bezuglova OS, Litvinov YuA (2020) The current state of the humus content of arable chernozems of the true steppes (the example of the Rostov region, Russia). South of Russia: ecology, development 15 (4): 99–113. https://doi.org/10.18470/1992-1098-2020-4-99-113[In Russian]

Gulyanov YuA (2019) Monitoring of the phytometric indications using innovative crop scanning methods. Taurida Herald of the Agrarian Sciences 3 (19): 64–76. https://elibrary.ru/item.asp?id=41445755[In Russian]

Gulyanov YuA, Dosov DZ, Umarova SA (2010) Efficiency of using bioclimatic resources in winter wheat cultivation in Orenburg region. Izvestia Orenburg State Agrarian University 2 (26): 48–50. https://www.elibrary.ru/item.asp?id=14999481 [In Russian]

EMISS State statistics / Crop yield (per harvested area) (2022) [Digital source] Available at: http:// www.fedstat.ru/indicator/31533 (accessed 22.05.2022)

Guo S, Zhang Z, Guo E, Fu Z, Gong J, Yang X (2022) Historical and projected impacts of climate change and technology on soybean yield in China. Agricultural Systems 203: 103522. https://doi.org/10.1016/j.agsy.2022.103522

Karataev M, Clarke M, Salnikov V, Bekseitova R, Nizamova M (2022) Monitoring climate change, drought conditions and wheat production in Eurasia: the

case study of Kazakhstan. Heliyon 8 (1): e08660. https://doi.org/10.1016/j.heliyon.2021.e08660
Khripunov AI, Obshchiya EN, Galushko NA (2021) Soil drifting in the conditions of slope lands. Proceedings of Gorsky State Agrarian University 58 (2): 38–43. https://www.elibrary.ru/item.asp?id=46221688 [In Russian]
Kincharov AI, Taranova TYu, Dyomina EA (2020) Specific reaction of spring soft wheat varieties to weather conditions. Bulliten KrasSAU 9 (162): 61–68. https://doi.org10.36718/1819-4036-2020-9-61-68 [In Russian]
Kiryushin VI (1993) The concept of adaptive landscape farming. Pushchinsky Scientific Center, Pushchino, 236 pp. [In Russian]
Kiryushin VI (2000) Ecologization of agriculture and technological policy. Publishing House of the TAA, Moscow, 473 pp. [In Russian]
Koshelev BS, Petsevich VV (2015) Influence of an environment on labor productivity in grain production of the Omsk region. The economy of agriculture in Russia 12: 55–59. https://www.elibrary.ru/item.asp?id=25137987 [In Russian]
Pavlova VN, Karachenkova AA (2020) Assessment of changes in climate-based productive of summer wheat in the main regions of its cultivation in Russia. Fundamental and applied climatology 4: 68–87. https://doi.org/10.21513/2410-8758-2020-4-68-87 [In Russian]
Perfileva NI, Korolyova LF (2015) Improvement of tillage systems in arid zone.Izvestiya of the Kabardino-Balkarian State Agrarian University named after V.M. Kokov 3 (9): 33–37. https://www.elibrary.ru/item.asp?id=48028175 [In Russian]
Precipitation and air temperature (2022) [Digital source] Available at: http://aisori-m.meteo.ru/waisori/select.xhtml (accessed 10.08.2022)
Rassypnov VA (2012) Agro-ecological zoning based on soil evaluation. Bulletin of Altai state agricultural university 21 (98): 039–041. https://www.elibrary.ru/item.asp?id=18725846 [In Russian]
Rusanov AM (2022) Natural rehabilitation of degraded steppe chernozems in the Volga-Ural interfluve area. Geography and natural resources 43 (3): 4651. https://www.elibrary.ru/item.asp?id=49396371 [In Russian]
Schierhorn F, Hofmann M, Adrian I, Bobojonov I, Muller D (2020) Spatially varying impacts of climate change on wheat and barley yields in Kazakhstan. Journal of Arid Environments 178: 104164. https://doi.org/10.1016/j.jaridenv.2020.104164
Selyaninov GT (1928) On the agricultural assessment of climate. Proceedings on agricultural meteorology 20: 165–177. [In Russian]
Shashko DI (1985) Taking into account the bioclimatic potential. Agriculture 4: 19–26. [In Russian]
Sieling K, Kage H (2022) Winter barley grown in a long-term field trial with a large variation in N supply: Grain yield, Yield components, protein concentration and their trends. European Journal of Agronomy 136: 126505. https://doi.org/10.1016/j.eja.2022.126505

Siptits SO (2018) Conceptual provisions on adaptation of regional agri-food systems to long-term climate change. Economy labor management in agriculture 4: 17–22. https://doi.org/10.33938/184-17 [In Russian]

Sokolova LV, Belyayev VI (2017) Forecasting model of spring soft wheat yield in temperate arid forest-outlier steppe of the Altai region. Bulletin of Altai state agricultural university 12 (158): 54–57. https://cyberleninka.ru/article/n/model-prognozirovaniya-urozhaynosti-yarovoy-myagkoy-pshenitsy-v-umerenno-zasushlivoy-kolochnoy-stepi-altayskogo-kraya/viewer [In Russian]

Tatarintsev LM, Tatarintsev VL, latysheva OA, Nikulin AA (2016) Vestnik of the Altai State Agrarian University 4 (138): 76–82. https://www-.elibrary.ru/item.asp?id=25895004 [in Russian]

Tikhonov VE (2000) Bioclimatic potential, its use and sustainability of grain production in the Southern Urals. Science to agriculture: Proceedings of the International Conference on increasing the sustainability of agricultural production, Orenburg, September 29-30, 1998. Publishing House of the Orenburg Research Agricaltural Institute, Orenburg, 26–36 p. [In Russian]

Vasilyev YuI, Belyakov AM, Nazarova MV (2020) Modeling of conection of crop yields of Volgograd region and precipitation in may and june. Izvestia of the Lower Volga Agro-University Complex 2 (58): 39–45. https://doi.org10.32786/2071-9485-2020-02-03 [In Russian]

Wang T, Li N, Li Y, Lin H, Yao N, Chen X, Liu D, Yu Q, Feng H (2022) Impact of climate variability on grain yields of spring and summer maize. Computers and Electronics in Agriculture 199: 107101. https://doi.org/10.1016/j.compag.2022.107101

Weather and climate (2022) [Digital source] Available at: http://www.pogodaiklimat.ru/history.php (accessed 10.03.2022 – 10.08.2022)

Zhukov AV, Polevoy AN, Vitchenko AN, Danielov SA (1989) Mathematical models for assessing agro-climatic resources. Hydrometeoizdat, Leningrad, 11–26 p. [In Russian]

Zhurina LL, Losev AP (2012) Agrometeorology. LLC "Quadro", St. Petersburg, 368 pp. [In Russian]