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PEDO-CLIMATIC CHANGES OF DRAINED FLOODPLAIN SOILS WITHIN THE FOREST-STEPPE ZONE OF THE REPUBLIC OF BASHKORTOSTAN (RUSSIA)

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Abstract: The article provides an assessment of climatic characteristics and changes in floodplain soils after the implementation of a drainage system. The study was conducted in the northern forest-steppe zone of the East European Plain (Republic of Bashkortostan, Russia). Through the analysis of long-term meteorological observations from 1961 to 2020, it was found that there was a steady increase in air temperature in all months and throughout the year, an increase in the period with positive temperatures, a slight increase in annual precipitation, and a reduction in precipitation during certain months of the warm season. Over the past 40 years, the drainage system has transformed the soil cover from Gleysols to Anthrosols, due to a decrease in the level of groundwater, agricultural use, as well as warming of the climate in the region. Thus, the transformation of soil cover can potentially contribute to climate change through the depletion of soil organic carbon stocks and increased greenhouse gas emissions. Nevertheless, currently, the natural and climatic conditions, morphological, water-physical, and agrochemical properties of Anthrosols allow for the production of two harvests of fodder crop (*Bromus inermis* L.) during the vegetation period. In general, the change in climatic indicators in the study area is consistent with the global trend. Our results underscore the sensitivity of soil systems to climatic variations and human activities, highlighting the need for local studies to understand regional and global environmental changes.

Keywords: climate change; agroclimatic resources; drainage reclamation; change in soil properties; yields

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1. Introduction

Numerous research (Abakumov et al., 2022; de Vries et al., 2013; Nizamutdinov et al., 2022) show the importance to society of the many ecosystem services provided by soil cover. At the same time, spatio-temporal studies are becoming increasingly important, with the help of which it is possible to assess the evolution of soils with intensive land use for agricultural production in a changing climate (Chalhoub et al., 2020; Yin et al., 2020).

Today, the world is facing an acute problem of shrinking fertile land suitable for growing crops (Lebbink et al., 2022; Osumanu & Ayamdoo, 2022; Pal et al., 2021; Schwaab et al., 2018). In this regard, it is necessary to include the agricultural use of land, the effective use of which requires various ameliorative measures. At the same time, ameliorative activities aimed at sustainably high yields of crops should not lead to the degradation of the soil cover (Miao & Xue, 2021; Singh, 2022).

In the Republic of Bashkortostan (Russia), two types of reclamation measures are the most common – irrigation and drainage. As of 2020, the area of reclaimed lands in the republic is 71,150 ha, of which 32,445 ha are under drainage and 38,705 ha are under irrigation (Adelmurzina et al., 2021). Drainage reclamation, aimed at improving the fertility of excessively wet lands, is the main factor that affects the water, air, thermal, and nutrient regime of the soil (Gramlich et al., 2018; Oliveira Filho et al., 2021; Sofia et al., 2019). While a number of studies were carried out to investigate the effect of irrigation on soil properties (Gabbasova et al., 2006; R. R. Suleymanov et al., 2021), the agroecosystems of drained soils in the republic were practically not studied. In this connection, the purpose of our research was the assessment of climatic characteristics and the soil cover functioning of Buraevskaya drainage system. The specific objectives of this study were: (1) to examine changes in climatic indicators for the period 1961–2020; (2) to conduct agrochemical analyses of soils; and (3) to identify the soils transformation. This study's novelty lies in its comprehensive approach, integrating climatic indicator analysis, and the identification of soil transformation. This holistic investigation provides a unique perspective on the interplay between climate change, soil health, and land-use dynamics, yielding valuable insights for sustainable agricultural practices and environmental management.

2. Objects and methods

2.1. Study area

The studies were conducted on Buraevskaya drainage system territory, located on the left bank on the river Bystry Tanyp floodplain (Figure 1). The drainage site is located between 81.1 and 97.4 m a.s.l. on a flat and high floodplain with a general northward slope (Khaziev & Mukatanov, 1985). Soil-forming rocks are dealluvial and alluvial carbonate clays and heavy loams. The drainage reclamation work was carried out in 1980. The drainage system was built specifically for growing various perennial crops. Before the construction of the drainage system, the studied area was pristine with natural herbaceous-grass vegetation, typical for the river floodplains of this natural-climatic zone (Kadilnikov, 1964; Khaziev & Mukatanov, 1985).

According to the physical-geographical zoning of the Republic of Bashkortostan, this territory is located in the northern forest-steppe zone within the Buysko-Tanypsky agro-soil district. The climate is temperate continental with warm summers and moderately cold winters (Galimova, 2017). The altitude varies from 65 to 300 m a.s.l. (Khaziev, 2012). The relief of the county is represented by undulating and hilly plains, characterized by a pronounced asymmetry. The southern and western slopes are steep, dissected by gullies and ravines, while the northern and eastern slopes are gentle. The area is composed of deposits of the Kungurian stage of the Permian system, which are represented by gypsum, anhydrite, limestone and dolomite. In some areas, there are Upper Permian sandy-clay sediments (Khaziev, 2012). Vegetation is represented by broadleaved forests (linden, oak, maple, elm, birch, and aspen) which are located on steep slopes, the tops of watersheds, gullies, and sinkholes. Unforested areas are mostly plowed. The natural herbaceous cover is represented by cereal-grass steppes. On the slopes of the southern exposure there are areas of cereal steppes (Khaziev, 1995). River valleys have wide floodplains and floodplain terraces. They are composed of quaternary loams, clays, sands, and pebbles. Soil cover is represented by gray forest soils (Haplic Luvisols) and podzolized chernozems (Luvic; IUSS Working Group WRB, 2015; R. Suleymanov et al., 2020).

2.2. Research methods

A total of 14 soil transects were set in the study area (Figure 1) in approximately the same locations as in the 1979 primary soil survey. Soil samples were collected from each soil pit from every genetic horizon over the width of the soil profile. Soil analyses were conducted using similar methods as in 1979. Soil samples were dried, processed, and sieved through a 0.25- or 1-mm sieve, depending on the agrochemical analysis technique. Agrochemical analyses were carried out using standard methods in soil science reported in Arinushkina (1970) and Sokolov (1975). The following soil properties were studied: soil organic carbon (SOC), alkaline hydrolysable nitrogen, available phosphorus, exchangeable potassium, exchange cations (Ca^{2+} and Mg^{2+}), dry residue and soil reaction (pH H_2O). Soil types name were presented according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

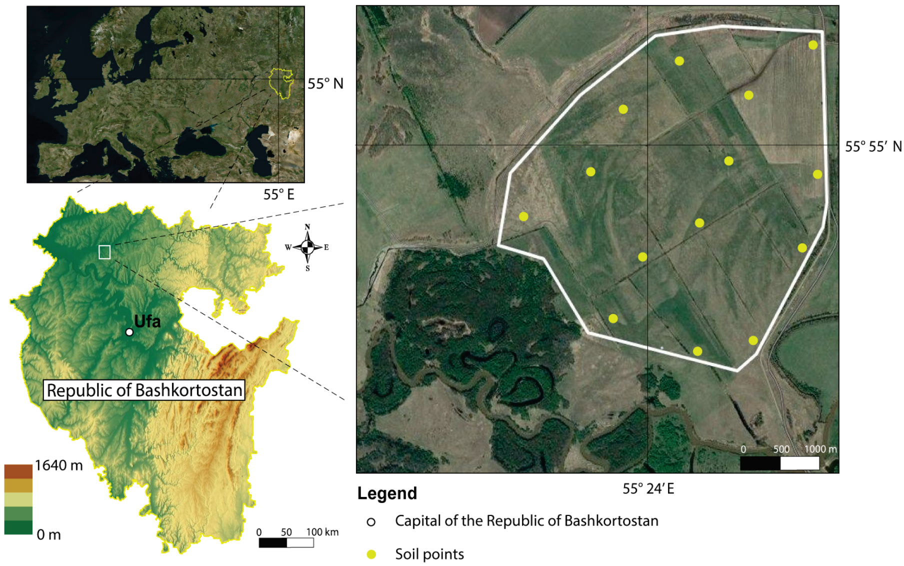

Figure 1. The map of the study plot location.

Note. Yellow line displays the border of the Republic of Bashkortostan, white line—the study plot.

Assessment of bioproductivity of monocultures (*Bromus inermis* L.) grown on a drained plot was carried out using the online platform for precision farming OneSoil (2017). This platform provides Normalized difference vegetation indices (NDVI) using remote sensing data.

For climate change assessment, the data of long-term observations of meteorological stations in the Yanaul, Askino, and Birsk settlements for the period 1961–2020 derived from the Bashkir Department of Hydrometeorology and Environmental Monitoring (n.d.) were analyzed. In addition, the basis climate norms recommended by the World Meteorological Organization (WMO) were calculated as a comparison (1961–1990, 1981–2010, and 1991–2020). In the case of analyzing the amount of precipitation, the period 1966–2020 was used because new requirements by their observations in the country were introduced. To analyze the temporal variability of climate variables, their basic characteristics were calculated: climatic norms for the entire study period (1961–2020) and for the periods recommended by the WMO, standard deviation for temperature and variation coefficient of precipitation sum. Assessment of regional climate changes was obtained using trend analysis. The angular coefficient of slope of the trend line (CSTL) characterizes the rate of value change, and the positive sign of the coefficient indicates growth (increase) of the value, whereas the negative sign indicates its decrease. The coefficient of determination (R^2) estimated the contribution of the linear trend to the overall variability of the indicator and its statistical significance (at the level of significance p = .05). To assess the territory moistening conditions, the evapotranspiration (E) was calculated according to Ivanov (1954; Equation 1), the hydrothermal coefficient (HTC) according to Selyaninov (1928; Equation 2), and the atmospheric moisture index (S) by Ped' (1975), determined for cold (S_{cp}; Equation 3) and warm (S_{wp}; Equation 4) periods of the year (Galimova et al., 2019; Perevedentsev et al., 2017). The considered hydrothermal indicators were used to determine arid conditions, drought, or excessive moisture during the active growing season.

$$E = 0.0018 \cdot (T + 25)^2 \cdot (100 - f) \tag{1}$$

Where T is average monthly air temperature (°C) and f is average monthly relative humidity (%).

$$HTC = \frac{R}{0.1 \Sigma T > 10} \tag{2}$$

Where $\Sigma\, T > 10$ °C is the sum of the average daily air temperatures above 10 °C; and R is the amount of precipitation over the same period (mm).

$$S_{\text{cp}} = \frac{\Delta T_i}{\Delta \sigma T_i} - \frac{\Delta R_i}{\Delta \sigma R_i} \tag{3}$$

$$S_{\text{wp}} = \frac{\Delta T_i}{\Delta \sigma T_i} - \frac{\Delta R_i}{\Delta \sigma R_i} \tag{4}$$

Where ΔT is air temperature anomaly, ΔR is precipitation anomaly, σT and σR is the mean square deviations of T and R in point i.

Gradations of HTC for determining moisture availability (degree of aridity) are as follows (Selyaninov, 1928): > 2.00 = *Over-wet*; 2.00–1.51 = *Excessive*; 1.50–1.41 = *Increased*; 1.40–1.11 = *Sufficient (optimal)*; 1.10–0.76 = *Insufficient*; 0.75–0.61 = *Low (mild drought)*; 0.60–0.41 = *Very low* *(medium drought)*; 0.40–0.21 = *Exceptionally low (severe drought*); and < 0.20 = *Catastrophically low (very severe drought)*.

Gradations of the aridity of Pedya index are as follows (Ped', 1975): (1) for the cold period (Galimova et al., 2019; Perevedentsev et al., 2017): $S_{cp} > 2$ = *winter is warm and snowy* and $S_{cp} < -2$ = *winter is cold with little snow*; and (2) for the warm period: $S_{wp} > 3$ = *severe drought*; $2 < S_{wp} < 3$ = *average drought*; $1 < S_{wp} < 2$ = *arid conditions (weak drought)*; $-1 < S_{wp} < 1$ = *normal humidification conditions*; $-2 < S_{wp} < -1$ = *humid conditions (weak excessive moisture)*; $-3 < S_{wp} < -2$ = *average excess moisture*; $S_{wp} < -3$ = *strong excessive hydration*.

3. Results and discussion

3.1. Climatic characteristics of the study area

3.1.1. Temperature regime

The average annual air temperature in the study region is 2.9 °C. The highest air temperature is observed in July (18.9 °C), and the lowest in January (−13.6 °C; Table 1). An analysis of the standard deviation of average monthly temperatures showed that the most stable months were July–September. The greatest temporal variation in temperature was typical for January and December. Time analysis revealed that in all months there was an increase in air temperature. Statistically significant trends were found in 6 months and a year (Table 1). The most significant increase in air temperature was in the period from January to March (0.51–0.71 °C/10 years).

Table 1. Statistics and indicators of variability of the main climatic variables for the research period (1961–2020)

Month	Air temperature			Precipitation amount			Hydrothermal conditions		
	Average (°C)	*SD* (°C)	*CSTL T* (°C/10 years)	Average (mm)	*V* (%)	*CSTL P* (mm/10 years)	*CSTL E* (mm/10 years)	*CSTL HTC* (pc./10 years)	*CSTL S* (pc./10 years)
I	−13.6	4.1	0.71*	36	44	0.65	–	–	0.26
II	−12.4	3.6	0.61*	28	52	0.70	–	–	0.26*
III	−5.7	2.8	0.51*	27	53	2.23	–	–	0.34*
IV	3.8	2.7	0.28	30	60	1.08	–	–	0.002
V	12.3	2.0	0.20	42	49	2.14	–	–	0.05
VI	16.7	2.0	0.22	62	51	2.90	–	–	0.05
VII	18.9	1.8	0.14	68	49	−5.72*	–	–	0.22
VIII	16.3	1.9	0.36*	58	45	1.29	–	–	0.12
IX	10.6	1.5	0.22*	57	51	−0.18	–	–	0.17
X	3.2	2.2	0.47*	61	43	−0.19	–	–	0.24
XI	−4.7	2.9	0.19	47	40	−0.44	–	–	0.05
XII	−10.8	3.8	0.21	39	44	0.74	–	–	0.14
Year	2.9	1.1	0.34*	555	15	7.00	12.1	0.02	0.30*

Note. Statistically significant trends at the confidence level $*p = .05$; *SD* = standard deviation; *V* = coefficient of variation; *CSTL* = slope coefficient of the trend line of temperature (*T*), precipitation (*P*), evaporation (*E*), Selyaninov hydrothermal coefficient (*HTC*), and Pedya index (*S*).

Figure 2 clearly shows that the average annual air temperature had a significant increase on average, for each decade it increased by 0.34 °C. At the same time, changes in the norms of this value were noticeable on the dynamics graph: 2.4 °C for the period 1961–1990, 3.1 °C for

1981–2010, and 3.4 °C for 1991–2020. It should also be noted that since the early 2000s, the average annual air temperature values rarely fell below 3 °C. In the last decade (2011–2020), in 6 years, its value exceeded 4 °C. The lowest temperatures were observed in the first half of the research period. The coldest years were 1969 (–0.7 °C), 1976 (0.8 °C), and 1986 (1.2 °C).

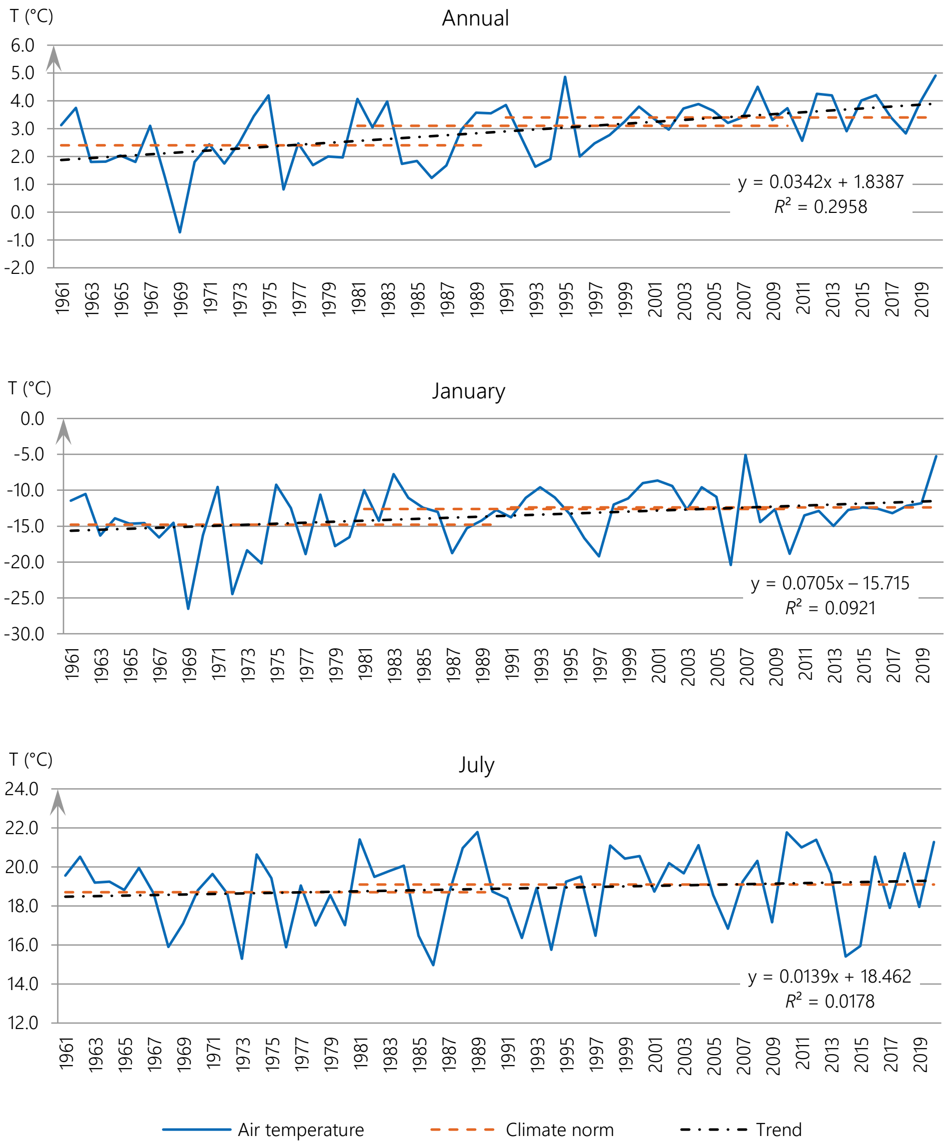

Figure 2. Long-term dynamics of the average annual temperature, average monthly air temperatures in the study area.

The character of heat supply affecting soil-forming processes over time depends not only on the warm season duration, but also on its structure, namely on the duration of periods with average daily temperature above 0, 5, 10, and 15 °C. Their average duration was 208, 170, 137, and 82 days, respectively. Analysis of variability of the duration of these periods showed (Figure 3) that the number of days in each of them increased (trends were statistically significant for all the periods). The largest increase was characteristic of the period above 0 °C (3.2 days/10 years) and above 15 °C (3.3 days/10 years).

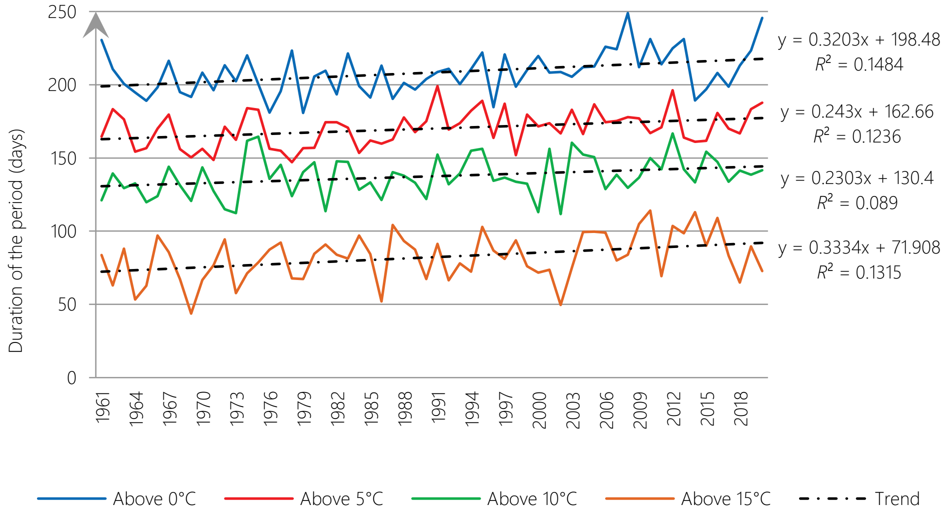

Figure 3. Long-term dynamics of the duration of periods with an average daily air temperature above 0, 5, 10, and 15 °C.

3.1.2. Precipitation regime

The distribution of precipitation over the territory and over time was more complex. In general, the annual amount of precipitation for the research area was 555 mm, of which 378 mm (68.1%) fell during the warm period and 177 mm (31.9%) during the cold period. The largest temporal spread of values, considering their coefficient of variation (Table 1 and Figure 4), was characteristic of precipitation during the warm period and per year. Considering the long-term dynamics of the amount of precipitation (Figure 4), it was found that in the period 1966–1990 it was 550 mm/year on average, 1981–2010—557 mm/year and 1991–2020—559 mm/year. The years with the highest precipitation were identified: 1990 (740 mm/year), 1994 (678 mm/year), 1978 (675 mm/year), and 1998 (657 mm/year).

The analysis of the *CSTL* calculations of monthly precipitation amounts showed (Table 1) that in some months there was a tendency for their reduction. Negative statistically significant trend was detected in July (–5.72 mm/10 years). Similar patterns for the entire territory of the Republic of Bashkortostan were previously identified (Galimova, 2020; Galimova & Silantyev, 2019). In general, *CSTL* of precipitation was 5.65 mm/10 years for the cold period, while for the warm period it was – 1.34 mm/10 years (Figure 4).

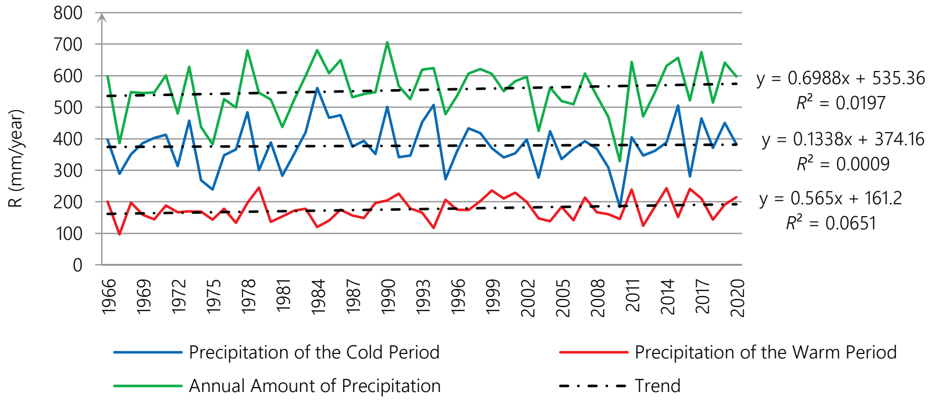

Figure 4. Long-term dynamics of the amount of atmospheric precipitation per year, warm and cold periods.

3.1.3. Moisture regime

The variability of heat and moisture availability, which was composed of the ratio of thermal conditions and precipitation, can be analyzed on the basis of evaporation and hydrothermal indices calculations. Figure 5 shows the consistency in the dynamics of evaporability and *HTC*: until the mid-1980s, the evaporability decreased, while the *HTC* increased. After 1985 the trends of these values were directly opposite. Generalizing the identified patterns, which were primarily associated with increasing air temperature and summer reduction of atmospheric moisture, we can state that there was an increase in arid conditions. It was found that since 2010 conditions of insufficient moisture have been formed at a long-term norm for the research area *HTC* = 1.2 (optimal moisture).

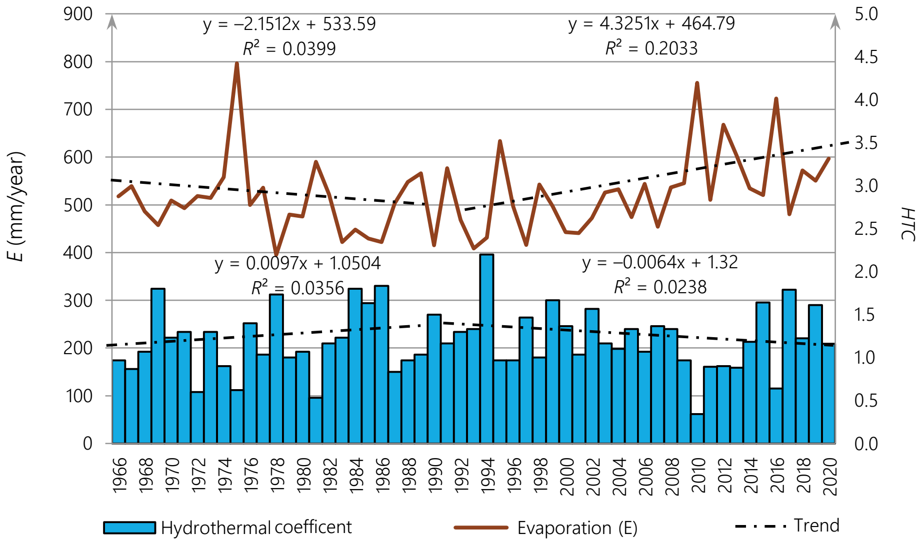

Figure 5. Long-term dynamics of evaporation (*E*) and hydrothermal coefficient (*HTC*).

For the warm period, a tendency to an increase in the atmospheric moisture (Pedya index) was revealed, i.e. conditions shifted to the "arid/weak drought" gradation (Figure 6; Galimova et al., 2019; Perevedentsev et al., 2017). The hydrothermal conditions of the cold period also undergo changes according to the index calculations. In cold periods, the frequency of winters with "warm and snowy" conditions began to increase. A similar trend was found in other parts of the republic. For instance, A. Suleymanov et al. (2022) investigated two periods (1937–1982 and 1982–2019) and found that increased mean annual temperature and decreased precipitation in summer contribute to the aridization in the steppe zone of the Trans-Ural region. Similarly, Bogdan et al. (2022) showed that an increase in air temperature accelerates the accumulation of positive temperatures, which eventually leads to an increase in the duration of the warm period. At the same time, the authors found that from 1966 to 1990 there was an increase in precipitation, and from 1991 to 2020 there was a decrease in precipitation, which contributed to an increase in aridity.

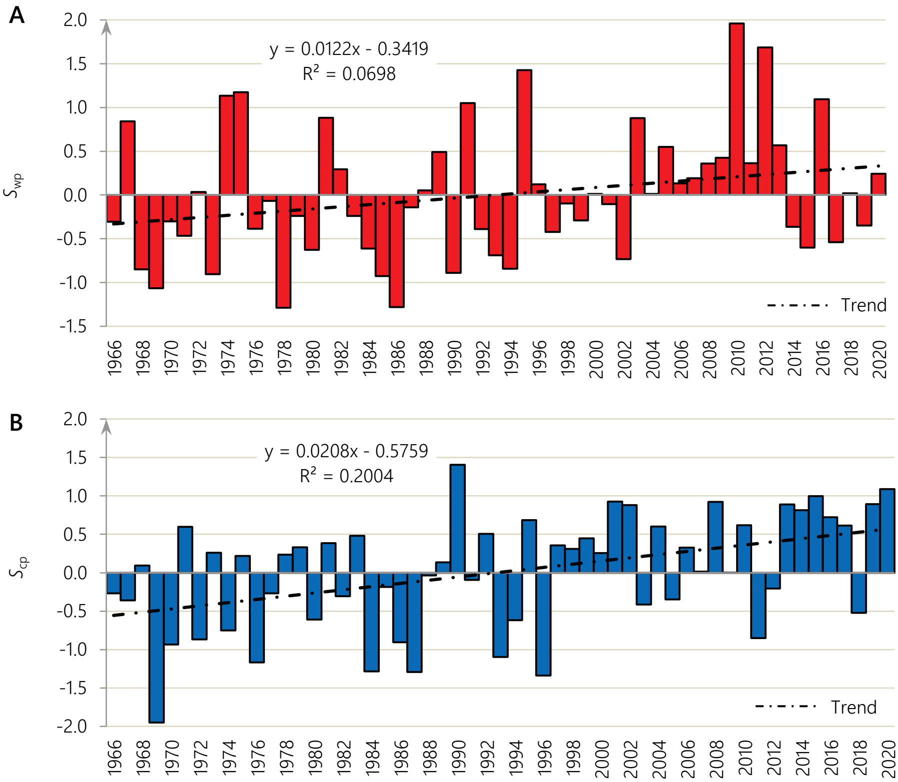

Figure 6. Long-term dynamics of the Pedya index for warm—S_{wp} (A) and cold—S_{cp} (B) periods.

3.2. Soil cover characteristics

Before the construction of the drainage system in the floodplain of the Bystry Tanyp River in 1980, the soil cover of the area was represented by Gleysols (Khaziev & Mukatanov, 1985). The formation of this soil took place when it was saturated with groundwater for a long time. Gleysols were characterized by the presence of the upper thick peated sod horizon, which transitioned to the gleyed humus-accumulative horizon. The depth of soil-ground waters was not less than 1 m.

Gleysols can be actively used for farming as arable land, for horticulture or grazing, but they are best suited for growing perennial grasses (Ball et al., 1989; Barbosa et al., 2021; Buchen et al., 2016). However, a major obstacle to the use of Gleysols in agriculture is the high groundwater level, so drainage reclamation is required to effectively use these soils (Brown et al., 2017).

The re-survey of the drained area in 2020 showed that the original Gleysols underwent significant, primarily morphological changes over the period of operation of the drainage system (Table 2). There was a significant decrease in the thickness of the peat sod horizon from 30–50 to 3–5 cm due to changes in redox conditions signs of gleying of the humus-accumulative horizon disappearance. At present, fodder crops (*Nromus inermis* L.) are grown in the studied area and cattle are grazing in some places. Since Gleysols have been significantly altered by anthropogenic activities and continue to be used in agricultural production, they can be classified as Anthrosols soil group according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

The upper humus-accumulative horizon (A, 3–37cm) of dark grey Anthrosols was characterized by a fine-grained crumbly structure and clay granulometric composition. This layer smoothly passes into the AB horizon (37–49 cm) of grey-brown color and granular-compound structure. The AB layer also smoothly passed into the illuvial B layer (49–84 cm), which was characterized by brown-compound structure with humus seeps from the overlying humus-accumulative horizons. Anthrosols formed on dealluvial and alluvial carbonate unstructured clays of dark brown color (cca, 84–120cm).

Table 2. Chemical properties of Anthrosols

Determination	Unit	Horizon, depth (cm)			
		A1	AB	B	cca
		3–37	37–49	49–84	84–120
pH H_2O	–	7.5±1.2	7.4±0.3	7.7±0.3	8.2±0.1
C org	g kg^{-1}	32.9±12.8	14.1±6.4	6.6±2.6	2.9±1.2
Nitrogen, alkaline hydrolysable	mg kg^{-1}	188±90	59±19	106±53	48±14
Phosphorus, Available (P_2O_5)	mg kg^{-1}	34.5±17.4	32.2±11.6	24.6±4.0	24.8±8.8
Potassium, Exchangeable (K_2O)	mg kg^{-1}	67.3±20.1	40.8±7.4	41.6±12.9	63.2±7.5
Ca^{2+}, Exchangeable	$cmol_{(+)}$ kg^{-1}	43.8±1.9	47.6±3.9	47.4±4.6	39.8±3.0
Mg^{2+}, Exchangeable	$cmol_{(+)}$ kg^{-1}	8.8±1.9	9.3±2.7	10.2±3.9	9.4±1.8
Dry residual	%	0.17±0.05	0.15±0.04	0.14±0.05	0.07±0.02

Note. ± = standard deviation; *n* = 14.

The Anthrosols profile was characterized by weakly alkaline reaction, but in the humus-accumulative horizons pH H_2O values were 7.4–7.5 and with depth it gradually increased to 8.2 levels. Among exchangeable cations, calcium prevails, the share of which exceeds the one of magnesium by about 4–5 times. The soil profile was not saline.

The maximum content of SOC content was observed in the A1 horizon (3–37 cm)—32.9 g kg^{-1} soil and decreased to 2.9 g kg^{-1} with depth. The content of nutrients (alkaline hydrolysable nitrogen, mobile phosphorus, and exchangeable potassium) in the soil profile was distributed unevenly, which was associated with the water regime of alluvial soils (Table 2). Earlier it was noted that in alluvial and drainage systems, nutrients were leached out and entered water sources (Arauzo & Valladolid, 2013; Brown et al., 2017; Rashmi et al., 2020). The degree of availability of Anthrosols nutrients in terms of the content of alkaline hydrolysable nitrogen was characterized as high, on exchangeable potassium—medium and mobile phosphorus—low (Kiryushin, 1996).

Previously it was demonstrated that changes in the hydrological regime of drained soils lead to changes in redox conditions (Labaz & Kabala, 2016; Vogelsang et al., 2016), gas regime (Valbuena-Parralejo et al., 2019), magnetic susceptibility (Shirzaditabar & Heck, 2021), biological activity (Moreira et al., 2021), and physico-chemical properties (Brown et al., 2017). Such a strong transformation of almost all the main soils properties and their agricultural use leads to the fact that drained soils lose their original nature, and their organic upper horizons are transformed into mineral ones (Labaz & Kabala, 2016; van Mourik & Ligtendag, 2015). The transformation process is accompanied by an increase in greenhouse gas emissions and a decrease in SOC content (Säurich et al., 2019; Wang et al., 2021).

Awnless brome *(Bromus inermis)*, as a fodder crop is widespread in the region, because it can withstand drought and prolonged overwatering and at the same time produce large amounts of green mass. Climatic conditions and peculiarities of growth and development of the plant allow getting two harvests per growing season. The average perennial yield of *Bromus inermis* in the forest-steppe zone of the republic for the first hay-crop is about 4t/ha, and for the second hay-crop it is about 2t/ha (Komissarov, 2011).

According to the OneSoil (2017) online-platform for precision farming, the NDVI index in the studied area on April 13, 2020 varied within the value range 0.1–0.3, then as effective temperatures increased and precipitation accumulated, by May 3 the index was already 0.3–0.6, by May 28—0.6–0.84, and by June 4—≥ 0.85, after which in some fields haymaking (first hay-crop) began and the index on the mowed plots fell to 0.3. After haymaking and harvesting, the index began to grow gradually and its maximum values increased to 0.6–0.8 by August 11, after which the second haymaking was carried out (second hay-crop). Thus, about 50 days passed from the beginning of the vegetation of the awnless brome grass to the first hay-crop, and about 60 days from the first hay-crop to the second one.

In 2021–2022, the dynamics of biomass growth was approximately identical to the year 2020, when there was a gradual increase of the vegetation index from May to June, then after the beginning of haymaking by the middle of June (first hay-crop) there was a decrease in the index. Further, the index also increased by the second hay-crop (the middle of August).

4. Conclusion

Studies investigating the impact of climate change on soil dynamics are highly relevant as they provide valuable insights for understanding and managing the consequences of climate change on soil resources, agricultural productivity, and ecosystem sustainability. In our study, we examined climate and soil changes, focusing on variations in temperature, precipitation patterns, and soil properties. The results revealed the steady growth in the average annual air temperature (0.34 °C/10 years) and slight increase in the annual amount of precipitation (7.0 mm/10 years). We assumed that these changes over a 40-year period, coupled with a decrease in groundwater levels due to drying, have significant consequences for the soil composition. Specifically, the soil has undergone a transformation from Gleysols to Anthrosols type due to the combined effects of reduced groundwater availability, agricultural practices, and climate warming. Moreover, these processes are accompanied by a loss of SOC and an increase in greenhouse gas emissions. However, despite the intensification of arid conditions, today the functioning of the drainage system allows for two harvests of fodder crops during the growing season.

Arguably, the regulation of the hydrological regime of the area and soil properties are the main factors determining the functioning of the dried ecosystem. Under the condition of technical maintenance of drainage system elements and application of soil-saving farming systems, the impact of climatic changes will be minimized. This transformation underscores the sensitivity of soil systems to climatic variations and human activities, highlighting the need for proactive management strategies to mitigate the impact on soil health and fertility.

Despite its valuable contributions, this study has certain limitations due to a huge gap between filed observations, because the soil transformation identification may not have taken into account intermediate changes or sudden disruptions in soil. Moreover, there may be errors of soil laboratory measurements in the past. To address these limitations and enhance the study's reliability, implementing a frequently monitoring system for climatic indicators and soil characteristics would be essential. This allows researchers to capture real-time data, providing a more accurate understanding of ongoing changes. Furthermore, local studies like these are crucial for providing the groundwork and data necessary for further assessments on a regional and global scale, enabling policymakers and researchers to develop effective strategies for sustainable agriculture, as well as for climate change adaptation and mitigation efforts.

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