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Changes in Climate and Bioclimatic Potential in the Steppe Zone of Ukraine

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ABSTRACT

To increase the level of management efficiency in the agricultural sector of the economy, it is necessary to substantiate environmental protection measures for the restoration and rational use of natural resources, to ensure the implementation of the sustainable environmental management principles, considering the spatio-temporal patterns of changes in climate and bioclimatic potential of the territory. Using the methods of multivariate statistics and time series forecasting, regularities of changes in climatic conditions in the Steppe zone of Ukraine for 1945–2019 were established, and a forecast of changes in the bioclimatic potential of the region until 2030 was made. It was established that during the research period the average annual air temperature increased by 3.5 °C. The amount of annual atmospheric precipitation varied within 186–778 mm with a variation level of 27.2%, in the last 20 years it was determined to decrease by 40% – to 500–300 mm. It has been proven that the inertial probability of repeating hot years is estimated at 0.58, and the possibility of repeating wet years at 0.46. As a result of forecasting, it was determined that if the trend of climatic conditions is maintained, there will be a stable trend-cyclic increase in the average annual air temperature by 0.06 °C per year and a decrease in the amount of annual precipitation by 62.0 mm per year. This resulted in an 18.7% increase in solar radiation on the soil surface and a 26.0% decrease in climatic losses on soil formation, which reduced the rate of the natural ability to reproduce soil fertility. In particular, the bioproductivity of plants decreased by 62.0%, and the probability of its further decrease by 20% is predicted. Over the past 20 years, the coefficient of natural humidification has decreased by 66.4%, and it is predicted to decrease by 20%. The obtained results confirm significant climatic changes and their negative manifestations on the reduction of bioclimatic potential in the Steppe zone of Ukraine, the deterioration of agricultural production conditions, the reduction of harvests, the self-regenerating and self-regulating function of steppe soils.

Keywords: climate, air temperature, precipitation, bioclimatic potential, retrospective analysis, forecasting, management, Steppe zone.

INTRODUCTION

Climate change is a global challenge of the 21st century, 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. Over the past 30 years, the frequency and intensity of dangerous weather phenomena has increased significantly, which lead to significant economic losses, threaten the stability of landscape and aquatic ecosystems, as well as the health and life of the population. It is predicted that the current direction of trend-cyclic climatic changes will be maintained (Wang et al. 2019, Felice et al. 2019, Dikshit et al. 2021), which cause significant changes in the functioning of natural and artificial ecosystems, an increase in the frequency of manifestations of dangerous processes and consequences, environmental degradation. Among the main causes of global climate change, world scientists include: the anthropogenic factor (Zhang et al. 2019, Christidis et al. 2021); increase in carbon dioxide in turnover (Paraschiv et al. 2020); radiative warming of the atmosphere due to the absorption of infrared radiation under the dominant influence of convective heat exchange (Sorokhtin et al. 2011); a change in currents in the Arctic Ocean (the cold Labrador Current in the Greenland area and the warm Gulf Stream), which leads to periodic catastrophic epochs of stable decrease and increase in the temperature regime in the Northern Hemisphere (Chaudhuri et al. 2009, Weiser et al. 2021). Climate at the regional level is formed under the influence of three most important factors: atmospheric circulation, solar insolation, and relief (Lisetskii et al. 2014). Preventive measures need to be defined and implemented, in particular: wide implementation of basin principles of environmental management, application of modern technologies to reduce emissions of carbon dioxide and pollutants into the atmosphere, reduction of arable land and increase of natural lands, use of alternative energy sources and energy supply technologies, the introduction of adaptive technologies and measures against uncontrolled climatic changes in various spheres of economic activity, etc.

An increase in anthropogenic load reduces the level of sustainability of the natural environment, which leads to manifestations of climatic change. Particularly negative manifestations of anthropogenic and climatic changes are concentrated in the Steppe zone (Lisetskii et al. 2016, Dudiak et al. 2019). The level of water resources supply and their quality has decreased significantly (Pichura et al. 2018, Pichura et al. 2020), the natural water network of small and medium-sized rivers has been destroyed by 60% (Oti et al. 2020, Lisetskii 2021), the frequency of droughts has increased (Assan et al. 2020, Ukrainskiy et al. 2020) and manifestations of erosion processes (Dudiak et al. 2019, 2020), the state of land resources deteriorated (Breus et al. 2019, 2020, Lisetskii et al. 2020), which led to a decrease in the yield of agricultural crops (Domaratskiy et al. 2020, Vdovenko et al. 2022). In order to increase the level of management efficiency in the agrarian sector of the economy (Vdovenko et al. 2015, Mayovets et al. 2021), it is necessary to substantiate environmental protection measures for the restoration and rational use of natural resources, to ensure the implementation of the principles of sustainable nature management, taking into account the spatio-temporal patterns of changes in climate and the bioclimatic potential of the territory. In particular, the internal integrity of the final part of the Holocene (the sub-Atlantic period) allows us to extend the averaged climatic data of the instrumental period to 2800 years ago (Ivanov et al. 1996), which provides the opportunity to carry out a historical reconstruction of climate-induced changes and a forecast of ecosystem functioning conditions. The analysis of available sources showed that the issues of study, retrospective analysis, modeling and forecasting of long-term changes in climate, and bioclimatic potential to develop and conduct new adaptation measures at different levels of management remain relevant and insufficiently researched.

The goal of the research is to establish patterns of changes and to make a forecast of climatic conditions and bioclimatic potential in the Steppe zone of Ukraine according to the following parameters: air temperature, precipitation, and watering of the territory, solar radiation, energy losses of the climate, plant bioproductivity.

MATERIAL AND METHODS

The research used the actual values of the surface air temperature (T, °C) and the amount of atmospheric precipitation (P, mm) according to the data of the Kherson station (latitude – 46°37’41”; longitude – 32°35’5”) for 75 years (1945–2019). Climatic norms for the observation period were: $\bar{T}$ = 9.8 °C; $\bar{P}$ = 415 mm. These parameters characterize the retrospective cyclical changes of climatic conditions in the Steppe zone of Ukraine.

Methods of additional climatic parameters calculating

Important derivative parameters of the climatic changes characteristics and assessment of their impact on the state of the environment are the parameters of the territory bioclimatic potential, including the value of the solar radiation balance (R, kcal/cm^2), energy losses of the climate for soil formation (Q, MJ/m^2), moisture (K_h) and plant bioproductivity (F, t/ha) of the territory.

The calculation of the solar radiation balance (R, kcal/cm^2) was carried out according to the formula (Lisetskii et al. 2014, Dudiak et al. 2019):

$$R = \frac{122.72T + 923.54}{41.868} \quad (1)$$

where: T is the value of the average annual temperature, °C.

To calculate the values of the energy losses of the climate on soil formation, the bioenergetic research method was used, which allows modeling cases of climate impacts, expressed in energy equivalents according to the formula (Volobuev 1974, Rasmussen 2007, Lisetskii et al. 2014, Pichura et al. 2021):

$$Q = 41.868R \cdot e^{\left(-18.8\frac{R^{0.73}}{P}\right)} \quad (2)$$

where: R – the balance of solar radiation, kcal/cm^2; P is the amount of atmospheric precipitation per year, mm.

Bioproductivity of plants (by mass of dry basis – F, t/ha) is calculated depending on the energy costs of the climate for soil formation according to the formula (Pichura 2020, 2021):

$$F = 0.3202 \cdot exp(0.003421 \cdot Q),\ r = 0.96 \quad (3)$$

An important indicator for determining the intensity of manifestations of dangerous storm washing and regulation of irrigation norms in the Steppe zone is the assessment of changes in the overall humidification of the climate according to the Vysotsky–Ivanov humidification coefficient (K_h), which is determined by the ratio of the sum of annual precipitation (Py) and annual evaporation (Ey) (Ivanov 1948):

$$K_h = \frac{Py}{Ey} \quad (4)$$

To estimate annual evaporation, we used the method (Kolomyts 2010), according to which evaporation depends on the average monthly air temperature of the warmest month (July – t_{max}) with high correlation coefficients $r = 0.94$ and determination $r^2 = 0.88$:

$$Ey = 1384 - 161.6t_{max} + 6.245t_{max}^2 \quad (5)$$

Zoning of the territory and establishment of time periods with different degrees of moisture is carried out according to gradation: $K_h > 1.0$ – territory (time period) with excessive moisture, K_h close to 1 – with optimal moisture, K_h = 1.0 – 0.6 – with unstable moisture, K_h = 0.6 – 0.3 – with insufficient hydration (Ivanov 1948).

Methods of retrospective analysis of climatic changes

For a detailed retrospective analysis, determination of temporal regularities in the formation of climatic conditions and assessment of the heterogeneity of time periods, the following research methods were used in the work: descriptive statistics, regression analysis and transformation of variables (method of difference integral curves of modular coefficients, level of security). The method of one-dimensional Fourier analysis was used in order to determine the cyclic components and identify the largest values of the periodogram of time series formation. The Markov chain method was used to estimate the probability of climate inertia (Sumner 1981). The probability of recurrence of periods with the corresponding conditions of climatic changes (H-hot, C-cold, D-dry, W-wet) was calculated by the methods of Gabriel and Neumann (Sumner 1981, Lisetskii et al. 2016). Anomalous manifestations of changes in climatic conditions are determined by the value of annual root mean square deviations from the value of the average multi-year norm: T, $P \geq \pm\sigma$ – strong anomalies and T, $P \geq \pm 2\sigma$ – very strong anomalies (Lisetskii et al. 2016).

Methods of predicting climate change

Retrospective research and forecasting of changes in climatic conditions was carried out taking into account the main components of time processes according to the formula:

$$T_t, P_t = Tr_t + S_t + C_t + \varepsilon_t \quad (6)$$

where: T_t, P_t – input data of climate change parameters;
Tr_t – feedback of the trend component;
S_t – feedback of the seasonal component;
C_t – response of the average annual cyclical component;
$\varepsilon_{t\text{-}n}$ – is the response of the probabilistic stochastic or unregulated component of climatic change.

To forecast changes in climatic conditions, an adaptive method of Holt-Winters time series analysis (three-parameter exponential smoothing) was used (Kleopatrov et al. 1973, Anderson

1976), which takes into account the patterns of retrospective climatic changes, including cyclic and trend components:

$$\begin{cases} L_t = \dfrac{\alpha Y_t}{C_{t-s}} + (1-\alpha)(L_{(t-1)} + T_{t-1}) \\ T_t = \beta(L_t - L_{t-1}) + (1-\beta)T_{t-1} \\ C_t = \gamma \dfrac{Y_t}{L_t} + (1-\gamma)S_{t-c} \\ \hat{Y}_{t+p} = (L_t + pT_t)C_{t-c+p} \end{cases} \quad (7)$$

where: Y_t – retrospective values of climate parameters (air temperature, precipitation);
L_t – the influence of retrospective values on the prognosis of $t+n$;
T_t – trend component;
C_t – cyclic component $t+n$;
$\hat{Y}_{t+n}$ – forecast value of climate parameters (air temperature, precipitation).

Working modules Time series and forecasting (TSF) of the licensed software product STATISTICA 10.0 were used for retrospective analysis and forecasting of climatic conditions in the Steppe zone of Ukraine.

RESULTS AND DISCUSSION

Due to extreme climatic conditions, manifestations of droughts and wind erosion, the Steppe zone of Ukraine is classified as a risky farming area. The territory is characterized by a high level of agricultural development, as of January 1, 2022, the area of agricultural land was 13,235.5 thousand hectares (21.92% of the total area of Ukraine). The area of nature-stabilizing lands is about 14.0%, including forests and other wooded areas make up only 6.10%, territories covered by surface water – 6.91%, the share of open wetlands – 0.97%. The high degree of agricultural development (77.83%) and plowed territory (66.76%) of the Steppe zone determines the low level of ecological sustainability of landscapes. More than 60% of the irrigated land area of Ukraine is in the territory of the Steppe zone, it is about 1324.1 thousand hectares, of which 461.2 thousand hectares (34.8%) are irrigated (Dudiak et al. 2021).

The extensive use of land resources in the Steppe zone led to an imbalance in the natural state of soil fertility, a significant deterioration of their fertility, a violation of the ecological balance of the environment, a decrease in the efficiency and speed of natural soil-forming processes, and an increase in energy costs for unstable crop yields (Breus et al. 2019, 2020, Dudiak et al. 2019, 2020, 2021, Pichura et al. 2021, Domaratskiy et al. 2022). In particular, negative ecological processes are enhanced by climatic changes and cause large-scale manifestations of wind erosion, alcolination and salinification of steppe soils, which confirms the relevance of a detailed retrospective study of climatic changes and its forecasting as a basis for the development of adaptive-cyclic environmental protection measures. These measures should consider zonal and intrazonal differences in landscape change, which are caused by various factors of their differentiation, in particular, in the northern parts, where precipitation exceeds the amount of evaporation, this is a thermal factor; in the southern ones – the moisturizing factor.

Retrospective analysis of climatic parameters

Research has established that in the Steppe zone of Ukraine, over the past 75 years, there has been a significant trend-cyclic increase in the average annual air temperature, an asynchronous decrease in the amount of annual precipitation, and a significant uneven seasonal distribution of it. The cyclical components of the long-term formation of climatic indicators were: air temperature – 8 years, the amount of precipitation – 11 years. The last 20 years (Fig. 1:1-a) are defined as the most extreme period in terms of the frequency of anomalous climatic manifestations, which increased 3 times (from 23% to 70%), which caused an increase in the temperature regime according to a cyclic-polynomial regularity ($r = 0.93$, $r^2 = 0.86$) and led to an increase in the average annual air temperature in the period 1945–2019 by 3.5 °C with an average growth rate of 0.047 °C per year. In the period 1998–2019 (Fig. 1:1-b), a systematic excess of the long-term norm by 0.7–2.5 °C or more is noted. As a result of the integral curve construction (Fig. 1:1-c), two main periods of the temperature conditions formation were determined: the first period (1945–1997) – cyclically stable temperature conditions, without a pronounced trend, the variation of the average annual air temperature was from 7.2 °C up to 10.9 °C, under the norm of 9.0 °C; the second period (1998–2019) – a stable trend-cyclical increase in the temperature conditions, the variation of the average annual air temperature was from 9.6 °C to 12.2 °C, against the norm of 11.1 °C. Over the entire period of observation, the level of variation in the temperature conditions was 12.7%, in particular, 20% (15 years) of abnormally hot years with an average annual temperature of 10.8 °C or more and 16% (12 years) of abnormally cold years with an average annual temperature of less than 8.4 °C were recorded (Fig. 1:1-d).

Changes in the temperature conditions are recorded throughout all seasons, the biggest changes are observed in the summer and autumn periods. Over the past 20 years of observations, the average air temperature in the summer period (VI–VIII months) has increased from 20.5 °C to 24.5 °C with a slight seasonal variation of 6.0%, in the autumn period, the temperature has increased from 9.5 °C to 12.5 °C with a variation

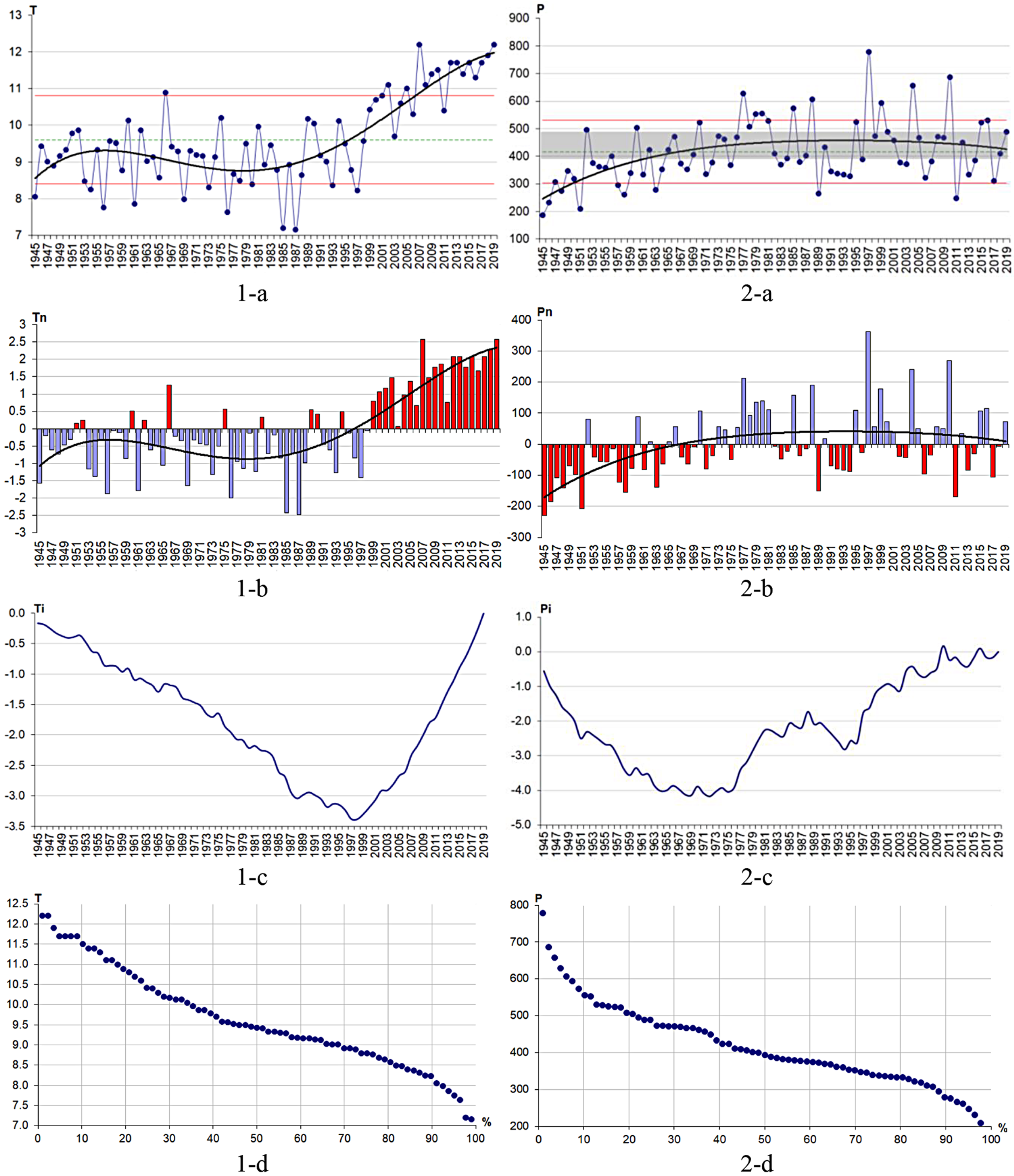

Figure 1. Characteristics of long-term climate changes in the Steppe zone of Ukraine in the period 1945–2019: 1 – air temperature (*T*, °C); 2 – precipitation (*P*, mm); (a) multi-year dynamics; (b) deviation relative to the long-term norm (T_n, P_n); (c) integral curves (T_i, P_i); (d) security level in %

level of 12.7%. The winter period is characterized by a significant variation of 25.0% and a slight upward trend in the change of the temperature regime, the average value of which increased from – 1.5 °C to 0 °C. In autumn, the air temperature increased from 10.0 °C to 12.0 °C with a variation level of 15.6% over 20 years. Comparative characteristics of monthly changes in minimum and maximum values are presented in Figure 2a – the periods 1945–1997 and Figure 2b – the period 1998–2019. Average monthly changes in the temperature conditions for two-hour slices are presented in Figure 2e.

The cyclicity of changes in atmospheric precipitation in the Steppe zone is in the asynchronous pattern of changes relative to the temperature regime. In the period 1945–2019, the amount of annual precipitation varied within 186–778

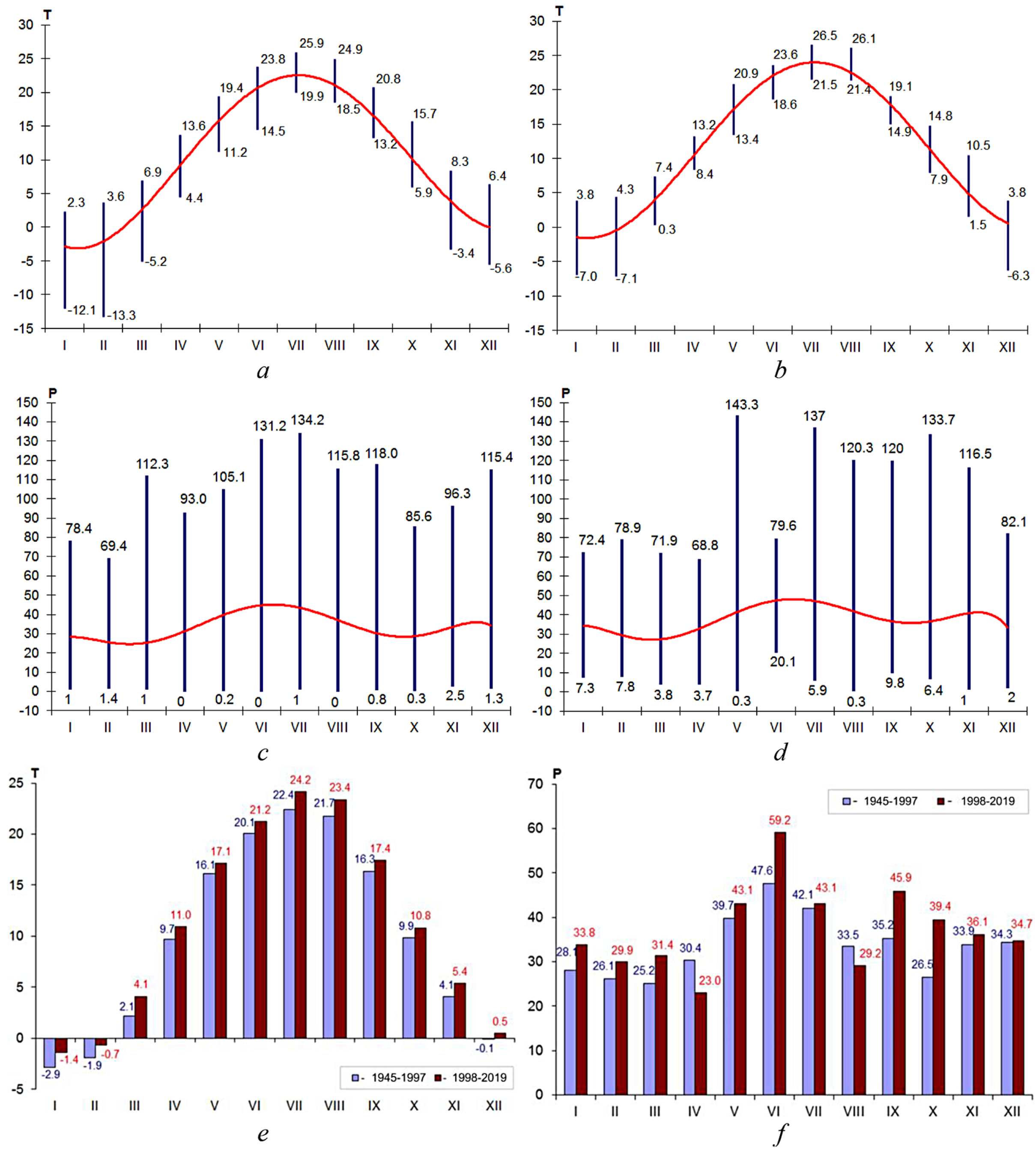

Figure 2. Comparative characteristics of seasonal changes in climatic conditions in the Steppe zone of Ukraine for two time periods: variation in air temperature, *T*, °C ((a) – 1945–1997; (b) 1998–2019); variation of atmospheric precipitation, P, mm ((c) – 1945-1997; (d) 1998-2019); (e) change in the average monthly air temperature; (f) change in monthly precipitation values

mm (Fig. 1:2-a) with a varying level of 27.2%. From 1945 to 1977, a stable trend-cyclic increase in the amount of atmospheric precipitation from 186 mm to 600 mm was recorded, this period is characterized by the largest number of years (23 years) with the amount of annual precipitation less than the multi-year norm (Fig. 1:2-b). Then, the second period of 1978–1996 was recorded, with a decrease in the amount of annual precipitation from 600 mm to 310 mm. The third period (1997–2019) is characterized by a negative trend and significant stochastic changes in the variation of natural moisture supply, anomalous manifestations of torrential nature, and unproductive precipitation, which lead to an increase in the frequency of manifestations in the winter-spring period of soil erosion and flooding of territories, in the growing season to shortage and uneven distribution of moisture. An increase in the amount of atmospheric precipitation at the beginning of the third period to 650–780 mm is marked by their further decrease by 40% – to 500–300 mm. Three periods of changes in atmospheric precipitation are well recorded on the integral curve (Fig. 1:2-c). The period 1945–2019 recorded 38 years (50.7%) with dry conditions (< 400 mm) of natural moisture supply (Fig. 1:2-d), 21 years (28.0%) with medium (400–500 mm), and 16 years (21.3%) with wet conditions. In particular, 12.0% (9 years) of abnormally dry years with rainfall of less than 300 mm per year and 13.3% (10 years) of abnormally wet years with annual precipitation of more than 530 mm were recorded. As a result of research, a strong inverse exponential dependence ($r = -0.94$) of the change in the number of days with dry spells from the change in the amount of atmospheric precipitation per year was established for the Steppe zone, the function has the following form: $y = 1500.2 \exp(-0.009P)$, $r^2 = 0.88$. An inverse linear dependence ($r = -0.76$) of an increase in the number of days with relative humidity of 30% from a decrease in the amount of annual precipitation was also established: $y = -0.1649P + 124.4$, $r^2 = 0.58$.

In comparison with the first period (1945–1997), in the second period (1998–2019), there is an increase in the average value of the amount of atmospheric precipitation in almost all months (Fig. 2f), mainly due to an increase in the minimum possible amount of atmospheric precipitation (Fig. 2d), an increase in the frequency of torrential precipitation in the spring-summer period from 15 to 30%, which causes a significant decrease in their productivity, an increase in soil erosion processes and an increase in the risk of ablation of agricultural crops from the fields, disruption of transpiration processes and an increase evaporation in the summer-autumn period.

Anomalous manifestations of seasonal climatic changes in the Steppe zone of Ukraine in the period 1945–2019 varies between 24–37% (Fig. 3). Significant anomalous manifestations of air temperature increase were recorded in the II, IV, V, VI, X and XI months, they vary from 15 to 20% (Fig. 3b). In particular, the highest frequency of abnormal manifestations (32–35%) of changes in the temperature regime is observed in the VI–IX and XII months, which have a greater impact on the average annual increase in air temperature. A significant variation of anomalous manifestations of the arrival of precipitation of a torrential nature is recorded in the III, IV, VII–X months (Fig. 3d), the most dangerous period of manifestations of anomalous variations in the arrival of minimum and maximum atmospheric precipitation is the spring-summer period – from 26% to 37% of cases observations for 1945–2019.

For graphic visualization (Fig. 4) and establishment of asynchronous patterns of changes in climatic parameters in the Steppe zone of Ukraine, statistical standardization of the values of the average annual air temperature (T_{st}, °C) and the amount of atmospheric precipitation (P_{st}, mm) was carried out according to the formula:

$$T_{st}, P_{st} = \frac{T_t, P_t - \bar{T}, \bar{P}}{T_{sd}, P_{sd}} \quad (8)$$

where: T_{st}, P_{st} – statistically standardized values of climatic parameters;
T_t, P_t – the actual value of the climate parameter at the t-moment of time, year;
$\bar{T}$, $\bar{P}$ – the average value of the climate parameter for 1945–2019; T_{sd}, P_{sd} – the value of the standard deviation of the climate parameter for 1945–2019.

As a result of calculations and the construction of a dynamic graph of statistically standardized values of climatic parameters, three asynchronous periods were determined (Fig. 4a): I period – 1945–1960, II period – 1961–2000, III period – 2001–2019. As a result of calculating the ratio of values (P_{st}/T_{st}; T_{st}/P_{st}) of climatic parameters (Fig. 4b), a significant asynchronous influence of air temperature on the amplitude of variational changes in atmospheric precipitation

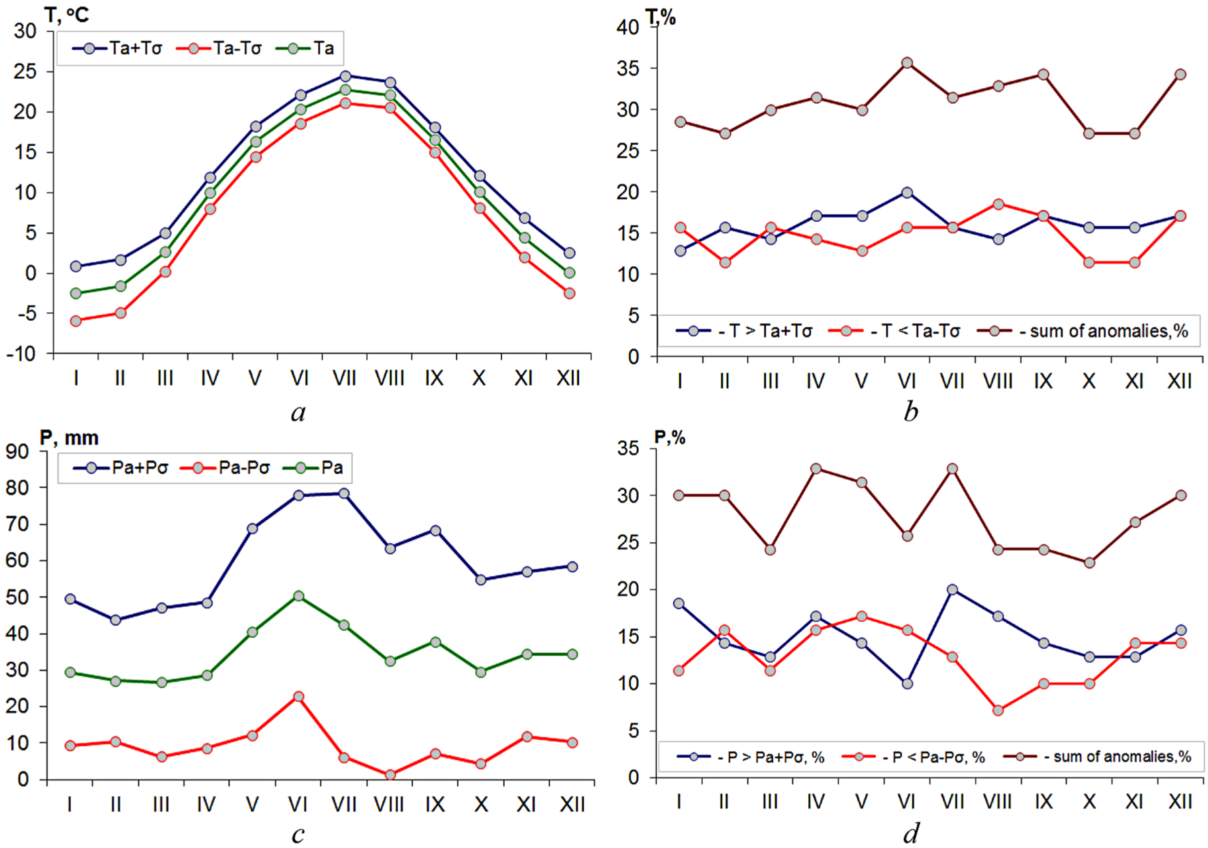

Figure 3. Anomalous manifestations of seasonal climatic changes in the Steppe zone of Ukraine in the period 1945–2019: (a) anomalous changes in average monthly air temperature values; (b) the percentage of abnormal air temperature values; (c) abnormal changes in monthly precipitation values; (d) the percentage of anomalous values of atmospheric precipitation

was determined. As a result of the transformation of the data and the calculation of their ratio, a graduated function of the cross-asynchronous interdependence of changes in the cyclicity and amplitude of the dynamics of the climatic parameters was established (Fig. 4c).

The probability of variational changes in the values of climatic parameters

The use of Markov chains makes it possible to determine the probability of annual inertia of climatic parameters based on data from 1945–2019. Thus, the probability of the recurrence of air temperature higher than the long-term norm was $P_T = 0.64$, and the amount of atmospheric precipitation for the year $P_P = 0.45$. The inertial probability of repeating hot (H) years is $P_{H1} = 0.58$, and hot years after cold $P_{H2} = 0.72$. Thus, the probability that a hot year will be followed by a cold one (C) $P_{C1} = 0.48$, and similarly the probability that one cold year will be followed by a cold year $P_{C2} = 0.36$. The inertial possibility of repeating wet (W) years was $P_{W1} = 0.46$, wet years after dry $P_{W2} = 0.43$. The probability that a wet year will be followed by a dry year (D) $P_{D1} = 0.58$ and similarly the probability that one dry year will be followed by a dry year $P_{D2} = 0.62$.

The probability of hot and rainy periods in t years is equal to the probability of cold and dry years, respectively, repeating every (t+1) year, i.e. (Sumner 1981):

$$P_{S(H\,;W)} = (1 - p_1)p_1^{t-1}$$
$$P_{S(C\,;D)} = p_2(1 - p_2)^{t-1} \qquad (9)$$

Therefore, the probability of a one-year isolated hot year is 0.52 p_1^{1-1}, the probability of a three-year hot period is 0.12, and a five-year one is 0.03. The probability of cold periods of the same duration is 0.60, 0.10, 0.02, respectively. The probability of a one-year isolated wet year is 0.50 p_1^{1-1}, the probability of a three-year wet period is 0.12, and a five-year one is 0.03. The probability of dry periods of the same duration is 0.60, 0.13, 0.04, respectively. Markov chains built based on meteorological observation proved data

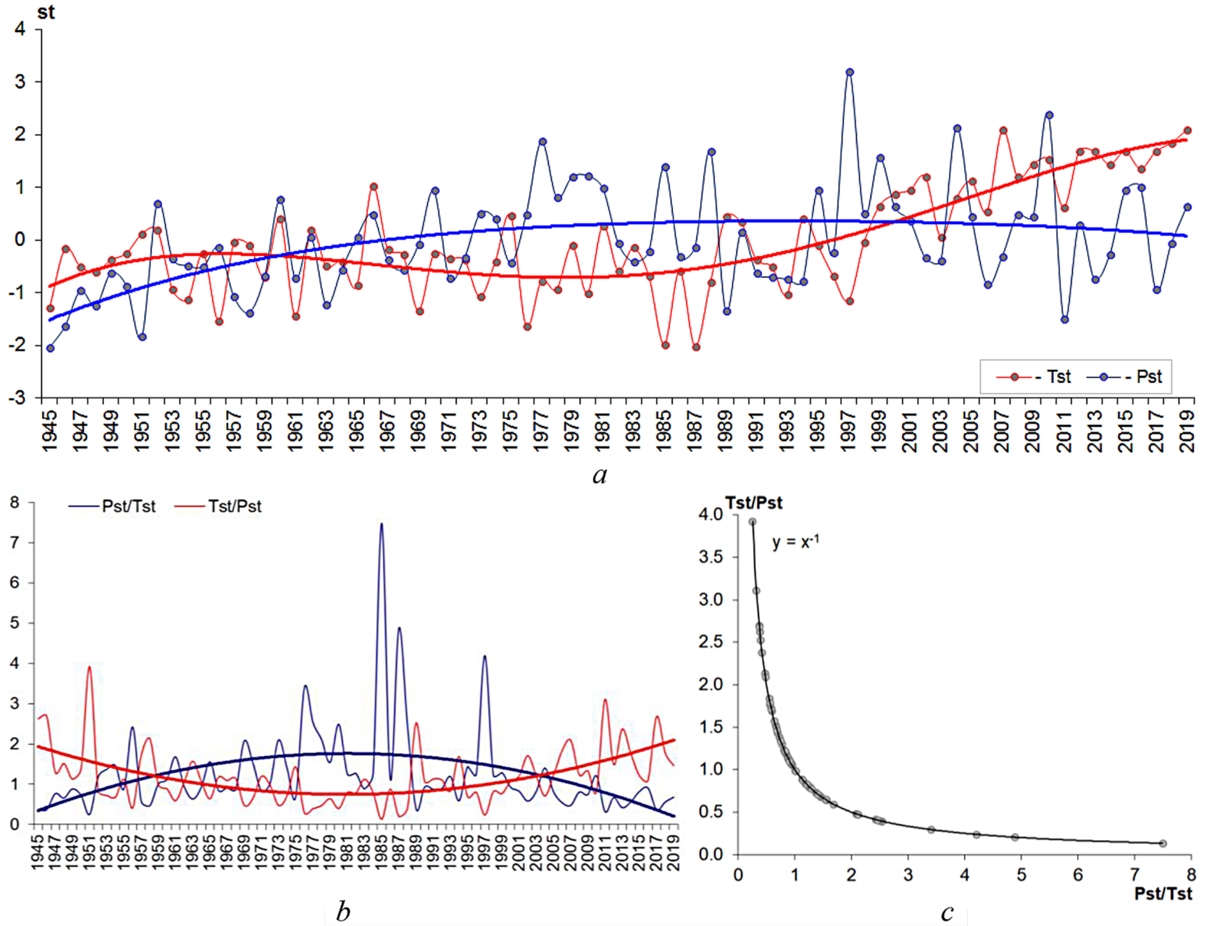

Figure 4. Asynchronous patterns of changes in climatic parameters in the Steppe zone of Ukraine: (a) dynamics of statistically standardized values of climatic parameters (air temperature (T_{st}, °C) and precipitation (P_{st}, mm)); (b) the dynamics of the ratio of climatic parameter values (P_{st}/T_{st}; T_{st}/P_{st}); (c) a function of the asynchronous ratio of climatic parameter values

that hot periods lasting 3–5 years are more likely than the same cold periods, and periods without rain lasting 3–5 years are more likely than periods with rain. This indicates an increase in the average annual air temperature and a decrease in the amount of annual precipitation in the Steppe zone of Ukraine.

Prediction of climatic parameters

As a result of modeling climate dynamics (T – air temperature, P – precipitation) in the Steppe zone (Fig. 5), predictive models of the following type were created:

$$\hat{T}_{t+n} = \left(\left(\frac{0.15T_t}{S_{t-9}} + 0.85\left(L_{(t-1)} + Tr_{t-1}\right) \right) + \atop + n(0.1(L_t - L_{t-1}) + 0.9Tr_{t-1}) \right) \cdot \left(0.15\frac{T_t}{L_t} + 0.85S_{t-9}\right)_{t-9+n} \quad (10)$$

$$\hat{P}_{t+n} = \left(\left(\frac{0.3P_t}{S_{t-11}} + 0.7\left(L_{(t-1)} + Tr_{t-1}\right) \right) + \atop + n(0.1(L_t - L_{t-1}) + 0.9Tr_{t-1}) \right) \cdot \left(0.1\frac{P_t}{L_t} + 0.9S_{t-11}\right)_{t-11+n} \quad (11)$$

where: L_t is the influence of retrospective climate formation data on the forecast period $t + n$; Tr_t – feedback of the trend component; S_t – the response of the seasonal component to the forecast period $t + n$; n = 10 years.

The error of models for forecasting climatic indicators is: air temperature – 7%, atmospheric precipitation – 20%.

It was determined that if the trend of climate conditions is maintained, with a probability of 93%, there will be a stable trend-cyclic increase in the average annual air temperature by 0.06 °C

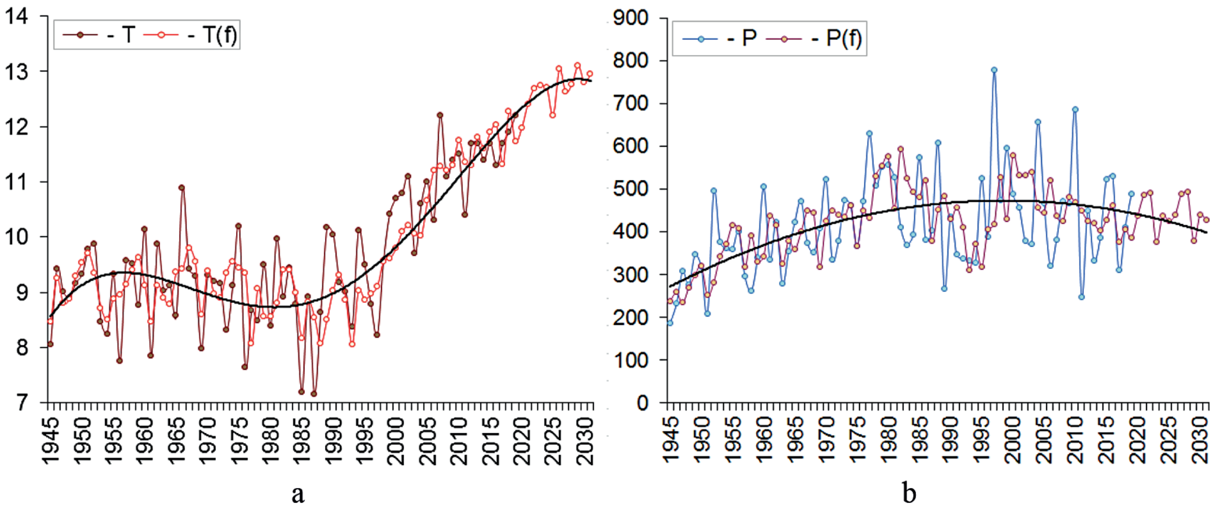

Figure 5. Dynamics and forecast of climatic changes in the Steppe zone of Ukraine until 2030: (a) average annual air temperature (actual values, *T,* °C; calculated values and forecast, *T(f)*, °C); (b) – sum of annual precipitation (actual values, *P,* mm; estimated values and forecast, *P(f),* mm)

per year and may reach 12.9±0.2 °C by 2030 (Fig. 5a), with a probability of 80%, a trend-cyclic decrease in the amount of annual precipitation is predicted by 62.0 mm per year, and by 2030 it may be 427±50 mm (Fig. 5b).

Retrospective analysis and the results of climatic parameters forecasting confirm the significant manifestations of climatic changes and the asynchronous dependence of the increase in air temperature on the decrease in precipitation. Insufficient moisture in the conditions of the Steppe zone and the need to increase yields stimulated the development of irrigated agriculture. Intensive farming on irrigated lands with the use of outdated equipment and technology led to irreversible processes of deterioration of their ecological and melioration condition (Pichura, Breus 2015, Martsinevskaya et al. 2018), flooding, salinification, and alkalization, overirrigation caused profile degradation of soils, excessive use of surface water resources.

Retrospective analysis and forecast of bioclimatic potential

Climatic changes are characterized by an uncontrolled dynamic process that affects the functioning of all components of the ecosystem, including the spatial-temporal differentiation of the bioclimatic potential of the Steppe zone of Ukraine. In particular, the climatic conditioning of the bioclimatic potential differentiation is an unstable time process, which is determined by cyclicity and amplitude, as well as a change in the trend of moisture supply and energy. Important derivative parameters of the climatic changes characteristics and assessment of their impact on the state of the environment are the parameters of the territory bioclimatic potential, including the value of solar radiation balance (*R*, kcal/cm^2), energy losses of the climate for soil formation (*Q*, MJ/m^2), moisture (K_h) and plant bio productivity (*F*, t/ha) of the territory.

The distribution of solar radiation is an important climatic indicator of biodiversity formation, the yield of agricultural crops, and the object of microclimate adjustment of agricultural landscapes. Spatial-temporal differentiation of solar radiation depends on the cyclic course of the temperature conditions and the morphometric characteristics of the terrain. In particular, the magnitude of the radiation balance is directly correlated with air temperature values and has cross-synchronous amplitudes of cyclic and trend components. During 1945–2019, the value of solar radiation balance increased by 18.7% (from 48.0 to 57.0 kcal/cm^2) with an average annual growth rate of 0.12 kcal/cm^2 per year (Fig. 6:1-a, b) an increase in the rate is predicted increase in solar radiation by 2030 almost twice – 0.25 kcal/cm^2 per year (from 57.0 to 60.0 kcal/cm^2). It was established that with an increase in the amount of solar radiation, the process of evaporation from the surface takes place more intensively, accordingly, this will lead to a decrease in the value of the soil moisture coefficient and a lack of harvest.

Cyclical changes in atmospheric precipitation and the asynchronous course of the arrival of

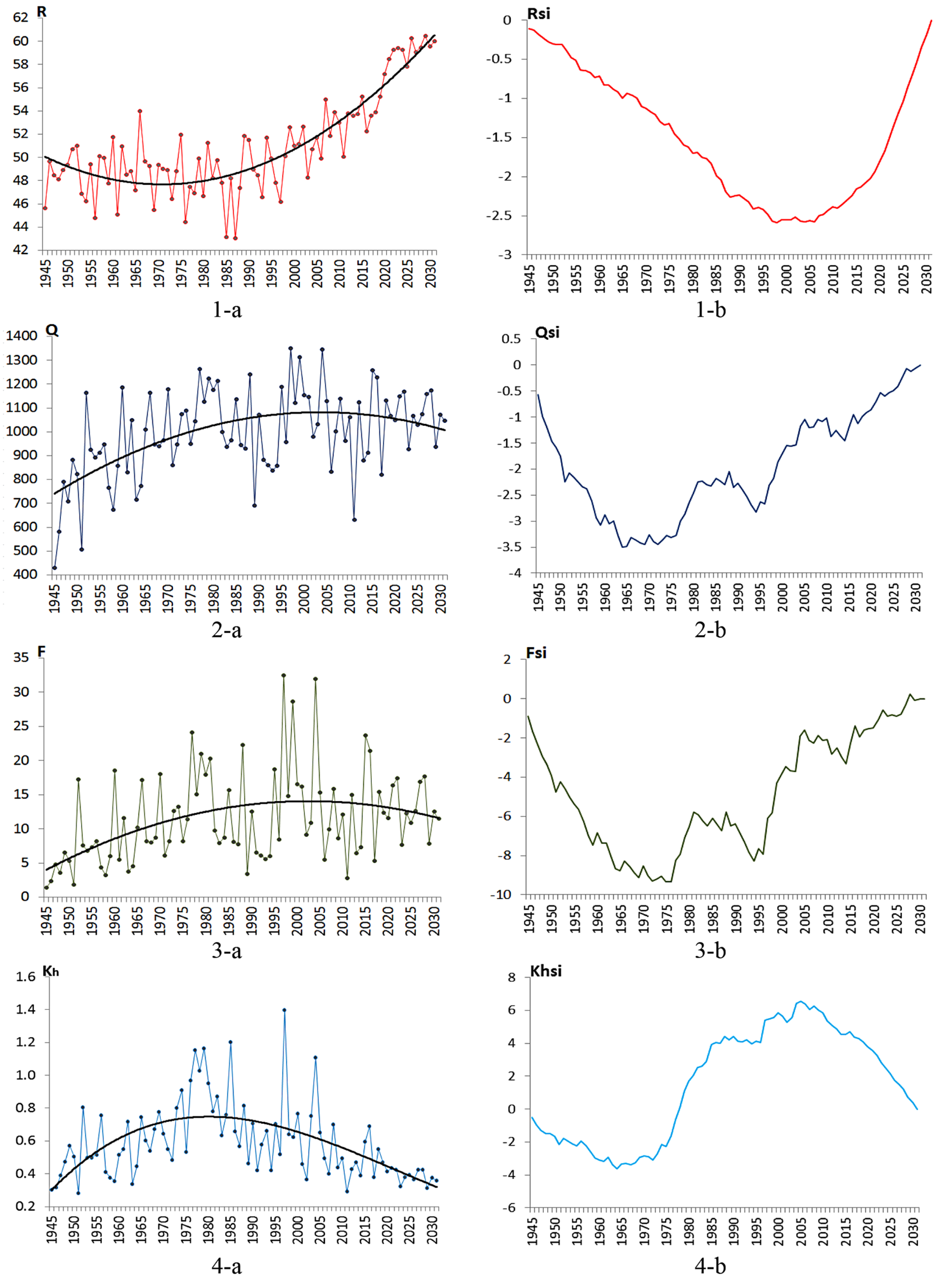

Figure 6. Dynamics and forecast of bioclimatic potential in the Steppe zone of Ukraine until 2030: 1 – the balance of solar radiation (*R*, kcal/cm^2); 2 – energy costs of the climate for soil formation (*Q*, MJ/m^2); 3 – bioclimatic potential (*F*, t/ha); 4 – Vysotsky-Ivanov humidification coefficient (K_h); (a) dynamics and forecast; (b) integral curve

solar radiation determine the reduction of energy losses of the climate on soil-forming processes. Thus, the annual climatic energy costs for soil formation (*Q*, MJ/m^2) within the territory of the Steppe zone for 1945–2019 varied from 430 to 1350 MJ/m^2 (Fig. 6:2-a,b), its minimum value was recorded in 1945, the maximum in 1997. It was established that from 1997 to 2019, annual climatic energy costs for soil formation decreased by 21.0% (from 1350 to 1070 MJ/m^2) with an average annual rate of decrease of 9.0 MJ/m^2 per year, in particular, a predicted to further decrease in climatic energy costs by 70.0 MJ/m^2 (from 1070 to 1000 MJ/m^2). Maintaining the negative trend towards a 26% decrease in the climatic conditioning of the soil-forming process will lead to a further decrease in the speed of the natural ability to reproduce soil fertility and an increase in the time for the conservation of degraded and unproductive agricultural lands.

The spatial heterogeneity of the soil cover within the Steppe zone is due to the interaction of bioclimatic, lithological, geomorphological, historical, and genetic factors. In particular, the temperature regime and the regime of moistening of the soil and air caused the zonal differentiation of the bioclimatic potential of soils, which characterizes the state of the atmosphere, as the main part of the environment and the functioning of soils. Under the conditions of constant climatic changes, the bioclimatic potential provides an opportunity to determine the spatio-temporal patterns of changes in the potential productivity of field crops, the rate of accumulation of organic matter, and the restoration of soil fertility. The bioclimatic potential of soils is determined by the amount of bioproductivity of plants.

It was determined that in the period 1945–2019, the value of plant bioproductivity (F) in the Steppe zone of Ukraine varied within 1.4-32.4 t/ha (Fig. 6:3-a,b), its minimum value was recorded in 1945, the maximum in 1997. In the period 1997-2019, the climatically determined bioproductivity of plants decreased by 62.0% (from 32.4 to 12.3 t/ha) with an average annual rate of decrease of 0.45 t/ha per year, in particular, a further decrease in bioproductivity is predicted plants by 2.5 t/ha (from 12.3 to 9.8 t/ha).

As a result of the calculations, it was determined that in the period 1945–2019, the value of the moisture coefficient (K_h) varied in the range of 0.28–1.40 (Fig. 6:4-a, b), and its minimum value was recorded in 1945, the maximum in 1997 In the period 1997–2019, the value of the humidity coefficient decreased by 66.4% (from 1.40 to 0.47) with an average annual rate of decrease of 0.018 per year, in particular, a further decrease in the value of the humidity coefficient by 0.09 (from 0.47 to 0.38) is predicted. According to Ivanov's classification, 8.0% of years with optimal and excessive moisture (K_h > 1.0), 38.7% with unstable (K_h = 1.0–0.6) and 53.3% with insufficient (K_h = 0.6–0.3) moisture were recorded.

CONCLUSIONS

As a result of retrospective analysis and forecasting, temporal patterns of climate changes and bioclimatic potential in the Steppe zone of Ukraine were established. The last 20 years have been defined as the most extreme period in terms of the anomalous climatic manifestation, which increased 3 times (from 23% to 70%). It was established that the average annual air temperature in the period 1945–2019 increased by 3.5 °C. The amount of annual atmospheric precipitation varied within 186–778 mm with a variation level of 27.2%, in the last 20 years, it was determined to decrease by 40% – to 500–300 mm. Three-time periods of asynchronous changes in air temperature and atmospheric precipitation established the approximated graduated function of the cross-asynchronous interdependence of changes in the cyclicity and amplitude of the dynamics of climatic parameters. With the use of Markov chains, the probability of annual inertia of climatic parameters was established, and it was proved that the inertial probability of repeating hot years is estimated at 0.58, and the possibility of repeating wet years at 0.46. This indicates a cyclical increase in the average annual air temperature and a decrease in the amount of annual precipitation in the Steppe zone of Ukraine. As a result of forecasting, it was determined that if the trend of climatic conditions is maintained, with a probability of 93%, there will be a stable trend-cyclical increase in the average annual air temperature by 0.06 °C per year and may reach 12.9±0.2 °C by 2030, with a probability of 80% is forecasted as a trend-cyclic decrease in the amount of annual precipitation by 62.0 mm per year and may amount to 427±50 mm by 2030. This resulted in an 18.7% increase in solar radiation on the soil surface and a 26.0% decrease in climatic losses in soil formation, which reduced the rate of the natural ability to reproduce soil fertility. In particular, plant bioproductivity decreased by 62.0% (from 32.4 to 12.3 t/ha) and the probability of its further decrease by 20% (from 12.3 to 9.8 t/ha) is predicted. Over the past 20 years, the coefficient of natural moisture has decreased by 66.4% (from 1.40 to 0.47) and it is predicted to decrease by another 20% (from 0.47 to 0.38). The obtained results confirm significant climatic changes and their negative manifestations on the reduction of bioclimatic potential in the Steppe zone of Ukraine, the deterioration of agricultural production conditions, the reduction of harvests, and the self-regenerating and self-regulating function of steppe soils. The presented results of the retrospective analysis and forecasting of climate changes should become the basis for the development and management of new adaptive climatic measures at different levels of management.

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