SUSTAINABLE AGRICULTURE IN UKRAINE

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The monograph is devoted to a comprehensive study of the state of in the Steppe zone of Ukraine and the development of approaches to improve agricultural techniques and measures aimed at balanced agricultural land use in the conditions of wartime and climate change. This investigation was supported by the Ministry of Education and Science of Ukraine for the projects: “Agroecological substantiation of system application of multifunctional growth-regulating preparations for cultivation the main field crops in the conditions of the Steppe zone of Ukraine” (state registration 0121U109552), 2021–2023; “Ecological and Economic Substantiation of the Development of Biological Technologies of Cultivation of the Main Field Crops in The Steppe Zone under the Conditions of Climate Change” (state registration 0122U000867), 2022–2023; “Formation of ecological and economic security of agrarian nature use for the implementation of the Association Agreement between Ukraine and the European Union” (state registration 0122U001170), 2022–2023; “Development of biological technologies for the cultivation of grain crops during the post-war reconstruction of Ukraine” (state registration 0123U101865), 2023–2024.

For specialists and practitioners in the field of land relations, ecology and natural resources, agrarian and water policy, graduate students and students of natural sciences.

CONTENT

INTRODUCTION

The growth of the Earth's population is a cause of increased demand for agricultural products. According to experts from the Food and Agriculture Organization (FAO), by 2050, the growth rates of agricultural production are expected to reach 60%. Solving food challenges is further complicated by climate change. In particular, climate changes over the past 20 years have been characterized by an increase in the average annual temperature by 2.0…2.5 °C and a decrease in total atmospheric precipitation by 120–180 mm, as well as an increased risk of extreme natural phenomena (hurricanes, hailstorms, floods, droughts, soil erosion, etc.) in all regions of Ukraine. This has led to an extension of the duration of periods of air-soil drought by 25–30%.

It is important to emphasize that under current conditions traditional agriculture reduces soil fertility and pollutes the environment with ballast compounds of synthetic fertilizers and pesticides. The assessment of pedogenesis rates under natural conditions has proved that soil formation processes occur slowly and soils are not regenerating. These findings determine the relevance of evaluating the state of soils from both a resource and ecological aspects. The agricultural land area in Ukraine amounts to 42.7 million hectares (70.8% of the country's land fund), including arable land covering 32.5 million hectares (78.4% of agricultural land). Each year, soils in Ukraine lose 400–500 kg/ha of organic matter. Over the past 100 years, humus content in Chernozem soils has decreased from 13–14% to 3–5%. The most influential factors contributing to landscape destruction and a significant decrease in soil fertility are water and wind erosion, resulting the annual loss of 300 to 600 million tons of soil within the country.

The annual increase in the area of eroded arable land in Ukraine reaches 60–80 thousand hectares. In particular, more than 1.1 million hectares of degraded, low-productive, and technogenically polluted lands, more than 140 thousand hectares of disturbed lands, and approximately 320 thousand hectares of low-productive agricultural lands that require conservation, reclamation, and improvement. Agriculture production losses due to soil degradation exceed 2.7–3.7 t/ha of grain, and a decrease of one centimeter of the humus horizon reduces the potential grain yields by 0.5–2.0 t/ha, while the sum of ecological and economic losses amount to $300 per hectare of arable land annually. As a result of neural forecasting, it has been established that in steppe soils, under the conditions of application the existing agricultural technologies, gradual dehumification is predicted: on non-irrigated lands – by 0.01%, and on irrigated lands, – by 0.03% per year. Additionally, this will lead to a reduction in the area of lands characterized by medium and high humus content. This trend proves the necessity of focusing the efforts on accelerating the transition to sustainable land use.

Ensuring sustainable land use has been complicated by the full-scale Russian invasion of Ukraine since February 24, 2022, which has resulted in significant human, environmental, and economic losses. According to the State Environmental Inspection of Ukraine, environmental damages exceed 36.56 billion US dollars, including 11.02 billion US dollars in losses of land resources and 54.16 billion US dollars in losses from soil pollution. In combat zones, the soil is found to contain petroleum products and heavy metals exceeding norms by 15–30 times. According to information from the Association of Sappers, approximately 4.8 million hectares of agricultural land in Ukraine are mined, and 13.6 million hectares require assessment for the presence of mines. This situation endangers global food security since 400 million people on Earth have access to food due to the export of Ukrainian agricultural products. Therefore, the necessity of developing sustainable land use requires scientific substantiation for increasing agricultural production under the condition of observing a socio-economic and ecological balance of land and water resources, preserving biodiversity, and ensuring food security.

Increasing the rate of agricultural production in Ukraine during wartime depends on the ability to improve agricultural techniques and measures aimed at balanced agricultural land use. In this context, it is important to achieve a prediction of the socio-ecological consequences of increased pressure on land resources and the economic feasibility of increasing crop yields. Solving problems of this nature can be achieved through the adoption of biologization of plant protection technologies. The use of biological preparations reduces the chemical load on the environment, enhances drought and stress resistance in crops, optimizes plant nutrition, stimulates root system development and above-ground vegetative mass, increases crop yields and product quality. Furthermore, biological plant protection agents improve plant immunity, increase the availability and speed of nutrient uptake by plants.

Biological agents contribute to the decomposition of plant residues, fix nitrogen, release phosphorus, fix potassium, increase the mobility of silicon, contribute to the biodegradation of chlorine-containing compounds and pesticide residues, improve soil structure and moisture availability.

Under the conditions of wartime and climate change, taking into account modern scientific and practical approaches to agriculture, it is urgent to seek adaptive elements in crop cultivation technologies that ensure the stabilization of productivity. In particular, the balancing of crop rotations and the development of new biological technologies for cultivating main field crops, which will provide both ecological and economic substantiation of adapting and growing new drought-resistant varieties and hybrids. The application of ecologically safe agricultural technologies based on biological methods of plant protection will be the basis for the ensuring Ukraine’s food security.

ENVIRONMENTAL AND ECONOMIC EFFECTS OF WATER AND DEFLATION DESTRUCTION OF STEPPE SOIL OF UKRAINE

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INTRODUCTION

Prognozed growth of world population in the next 30 years is the reason for the increase in demand for agricultural products, resulting in the need to increase its production by 60% (Levers et al., 2016). The major grain exporters on the world market in the last 10 years are the USA, Canada, Australia, Argentina, countries of the European Union, Ukraine. These countries together provide about 80% of grain volume. Ukraine takes 3rd place in barley export (16.7% of the world market), 4th place in corn export (6%), 6th place in wheat export (5.4%) (Lisetskii et al., 2017). The area of agricultural lands of Ukraine is 42.7 million ha (70.8% of the land fund of the country), including the arable land area of 32.5 million ha (78.4% of agricultural land). The prevailing type of soil in Ukraine is chernozem, the area of which is around 17.4 million ha (40.7% of agricultural land). The area of agricultural land per person is 0.9 ha, including arable land – 0.7 ha, which is 2.5 times higher than the average value for European countries (Extended five-year report…, 2017). The plowing of the territory of Ukraine is 54.6%, which has led to the manifestation of erosion processes in large areas, a significant violation of the ecological stability of landscapes and a significant reduction in soil fertility.

Water and wind erosion are the most powerful factors in the destruction of landscapes, the reason for the decrease of soil fertility and breach of food security in the country. In Ukraine about 13.3 million ha (31.3%) of agricultural land, including 32.6% (10.6 million ha) of arable land are constantly affected by the negative effects of water erosion (Petrichenko et al., 2013;

Balyuk et al., 2017). Land that is medium and highly eroded due to water takes 4.5 million ha (13.8% of arable land), 1.5% of which has completely lost the humus horizon. 18.5% of arable land is systematically affected by wind erosion, 61.5% is affected by dust storms (Bulygin et al., 2016). Generally, the annual growth of the eroded arable land reaches 60–80 thousand ha in Ukraine. In general, more than 1.1 million ha of land belong to the degraded, low productive and technologically contaminated land. More than 140 thousand ha belong to the category of disturbed land. About 320 thousand ha belong to low productive land primarily subject to conservation, require restoration and improvement (Svetlitchnyi, 2009; Balyuk et al., 2017).

Erosion processes lead to deterioration in physical properties of the soil, decrease and complete destruction of humus horizon, resulting in a significant decrease in the humus and macro/micro elements, deterioration of soil fertility, which causes decrease in the value of bonitet of zonal soils, decrease in crop yields up to 60% and increase of costs for agrotechnological activities (Lisetskii et al., 2012; Pichura et al., 2017; Tarariko et al., 2017). As a result of studies (Baliuk et al., 2010; Voloshchuk et al., 2014), it was found that the scope of humus removal is 310–460 kg per 1 ha of arable land, nitrogen – 9.0–28.0 kg/ha, phosphorus – 21–28 kg/ha, potassium – 180–370 kg/ha. Over the past 100 years the humus content in chernozems has decreased from 13–14% to 3–5%.

Irrational land use and abnormal manifestations of climatic conditions (water and wind erosion) in the steppe zone of Ukraine over the past 40 years have led to a decrease in the content of humus by 0.36%, exchange potassium by 18%, mobile phosphorus by 34.17%, nitrification of nitrogen by 17.0% (Pichura, 2015; Domaratskii et al., 2018, 2019) in average. According to the results of neuromodeling, it is predicted (Lisetskii et al., 2017) a gradual decrease in the humus content in the soil layer 0–20 cm (on non-irrigated lands – by 0.01% per year, on irrigated lands – by 0.03% in year) and reduction of land areas, which are characterized by medium and high humus content. This data shows significant deviations as it requires 25–30 years for the increase of humus in the soil by 0.1% in natural conditions (Lasanta et al., 2019; Jensena et al., 2020). Significant negative influence of erosion appears in all components of landscape structures, resulting in agricultural production losses that exceed 0.27–0.37 t/ha of grain units (Sartori et al., 2019). With the loss of each centimeter of humus horizon, the potential grain yield is reduced by 0.5–2.0 kg/ha, and the environmental and economic losses due to erosion annually make more than 300 USD per 1 ha of arable land (Sartori et al., 2019).

Irrigation areas have irrigation erosion, which is the result of sprinkler method application. The area of irrigated lands of Ukraine is 2,170.5 thousand hectares, of which 23.3% is irrigated area (Lisetskii et al., 2016). More than 60% of the area of irrigated land is located in the Steppe zone, excluding the temporarily occupied territories, it is about 1,324.1 thousand hectares, of which 461.2 thousand hectares (34.8%) are irrigated. Breached irrigation regime leads to a rise in groundwater, salinization and alkalinization of soils. This is a confirmation of the fact that the preliminary studies have shown that accelerated erosion occurs in areas with increased anthropogenic load. It leads to ecological disturbances of the natural balance of territorial ecosystems (Achasov et al., 2000; Li et al., 2020; Benauda et al., 2020).

Therefore, it is necessary to determine the influence of factors and processes of water and wind erosion, frequency of its influence, diversity of the spatial distribution on the economic efficiency of agriculture, justification of environmental measures and restrictions in the use of land resources through implementation of effective land management and implementation of adaptive and landscape erosion control organization of the territory with elements of conservation agriculture. It will strengthen the country's food security and create environmentally safe conditions for carrying out business activities and providing the framework for the implementation of sustainable land use.

MATERIALS AND METHODS

Research and assessment of ecological and economic consequences of water-deflation destruction of steppe soils of Ukraine was carried out in several stages (Fig. 1, see p. 8) with systems using the necessary scientific methods. At the first stage, the modeling of spatial differentiation of water (State Standard 17.4.4.03-86 …, 1986; Renard et al., 1997; Chen et al., 2017; Phinzi et al., 2019) and wind (Mozheiko et al., 1980; Achasov et al., 2000; Bulyhin, 2005) erosion manifestations was carried out to calculate the losses of soil (t/ha) and to determine the degree of their degradation. At the second stage, soil-climatic bonitet of zonal soils (points) is carried out to determine their natural fertility (t/ha) (Karmanov et al., 1980, 2012, 2013). At the third stage, the spatial adjustment of the differentiation of natural soil fertility to the negative effect of erosion processes was carried out. This made it possible to calculate crop losses and total monetary losses from water and wind erosion. The simulation results were used to determine the spatial differentiation of soil quality characteristics and to establish their erosion hazard in order to develop and implement measures of adaptive-landscape anti-erosion design with elements of soil-protective agriculture.

The study was conducted on the territory of the steppe zone of Ukraine (Dnipropetrovsk, Zaporizhzhia, Kirovohrad, Mykolaiv, Odesa, Kherson regions) (Fig. 2, see p. 9) (total area is 167.4 thousand km^2), including the area of agricultural land (131.6 thousand km^2). Agricultural development of the region varies within 20–97%.

Methods for the first stage of research. For modeling of erosion losses of soils due to water, the modified empirical and statistical model RUSLE (Revised Universal Soil Loss Equation) was used (State Standard 17.4.4.03-86 …, 1986; Renard et al., 1997; Chen et al., 2017; Phinzi et al., 2019):

$$A = R \times K \times LS \times C \times P \, , \tag{1}$$

where *A* is the average multiyear value of erosion due to runoff (rain), t/ha/year; *R* is the average multiyear erosive potential of rainfall (*EPR*), conditional unit; *K* is the coefficients of soil cover erodibility, t/ha per year; *LS* is the terrain factor; *C* is the erosion index of crop or crop rotation as a whole; *P* is the coefficient of soil protective effectiveness of erosion control activities.

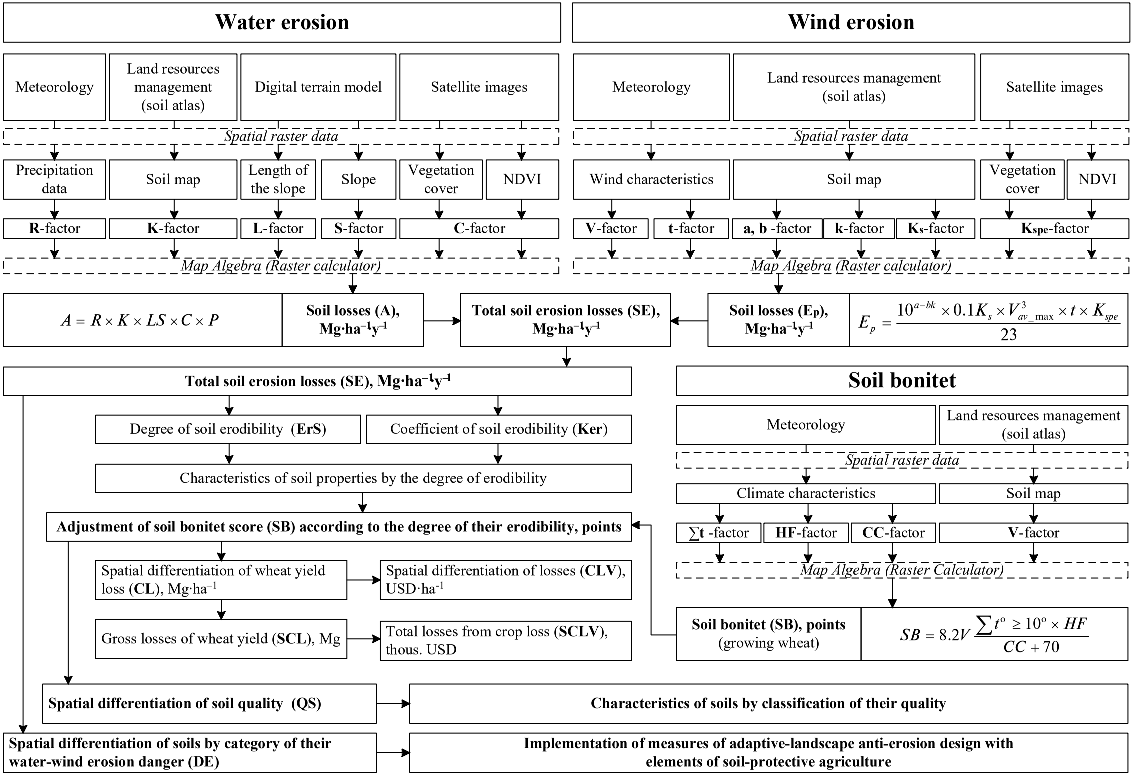


Figure 1. Structural and logical methodological scheme of research of ecological and economic consequences of water-deflation destruction of soils

The RUSLE model is used in the environment of GIS licensed software for the ArcGIS 10.1. For this purpose, a raster model (spatial resolution 30×30 m) of each integrated factor of model of water erosion of soils in the steppe zone of Ukraine was created. Spatial model of average annual potential rainfall (*R*) was obtained on the basis of extrapolation of decompositions of meteorological cartograms according to 47 meteorological stations in the period 1990–2018 using geostatistical method of kriging (Hu et al., 2020).

In areas where no rain intensity data are available, it is advisable to use a formula involving actual meteorological measurement data (Erdogan et al., 2012):

$$R = \sum_{i=1}^{12} 1.735 \times 10^{1.5\,Log(pi^2)/P - 0.8188}, \qquad (2)$$

where pi – monthly average precipitation, mm; P – average annual precipitation, mm.

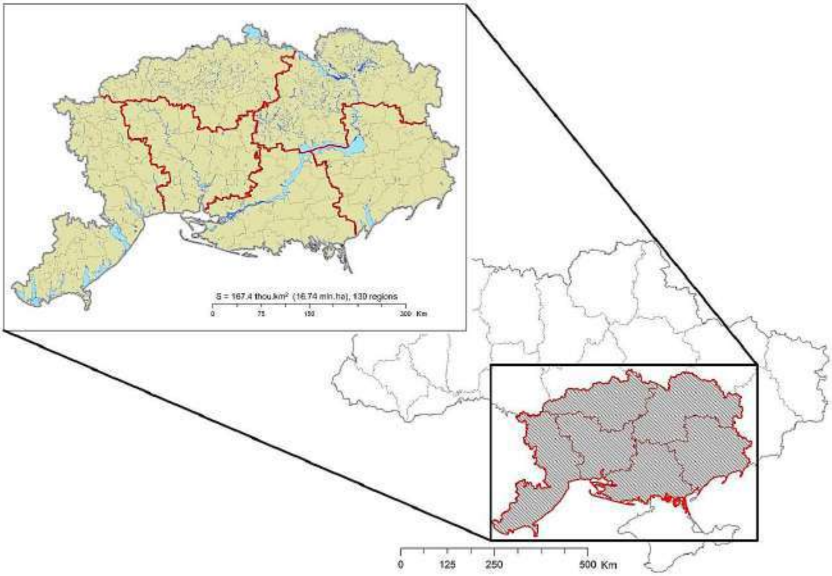


Figure 2. Spatial characteristic of studied territory of the steppe zone of Ukraine

Vectorization of soil maps of the steppe of Ukraine (Fig. 3, see p. 11) was carried out when determining factor of soil cover erodibility or the factor of soil compliance to erosion processes (*K*). The parameter *K* was calculated (Grushetsky et al., 1990) and spatial raster model was obtained for each soil type according to its granulometric composition in line with the soil erodibility coefficients (t/ha per year) (Table 1).

Table 1. Coefficients of soil cover erodibility (*K*), t/ha

The main types of soil	**Coefficients of soil cover erodibility**			
	Granulometric composition of soils			
	heavy loam	**medium loam**	**light loam**	**sandy loam**
Sod podzolic on cover sediments	3.0	3.3	3.7	3.6
Light gray forest	2.7	3.0	3.4	3.6
Gray and dark gray forest	2.0	2.4	2.8	—
Chernozems podzolized	1.2	1.6	1.9	1.9
Chernozems typical	1.4	1.8	2.0	—
Chernozems common	1.2	1.6	1.8	1.8
Chernozems southern	1.5	1.6	2.0	—
Chernozems carbonate	1.5	—	—	—
Dark chestnut	—	2.1	—	—
Dark chestnut carbonate	2.4	2.6	—	—
Chestnut	2.5	2.6	—	2.3
Chestnut carbonate	2.6	2.8	2.3	—
Light chestnut	2.6	2.5	3.0	2.0

Erosion potential of the terrain (LS) was evaluated using spatial analysis of hydrological correct digital elevation model (DEM) with the spatial resolution 30×30 m (https://earthexplorer.usgs.gov/). Morphometric characteristics of the relief were defined and raster cartograms of lengths (L) and slopes (S) of the surface were constructed using the working module Hydrology tools of the Spatial Analyst Tools and Surface of the Spatial Analyst Tools. Then the value LS for each pixel was calculated using the module Raster Calculator according to the formula (State Standard 17.4.4.03-86 …, 1986):

$$LS = L^{0.5} \times (0.0011 \times S^2 + 0.0078 \times S + 0.0111)\ . \qquad (3)$$

The coefficient of the vegetation cover (C) together with LS factor is most sensitive to soil loss (Enkobi et al., 1994; Biesemans et al., 2000). Soil loss is being reduced with increasing vegetation. The data of earth remote sensing (ERS) of correctly calibrated satellite image of Landsat-8 with geometric resolution (spatial resolution) ~30×30 m as of March and August 2018 was used to determine the factor C. Generation of values of the factor C was carried out on the basis of dimensionless index NDVI (normalized differential vegetation index), this formula was used therefore (Van Leeuwen et al., 2004):

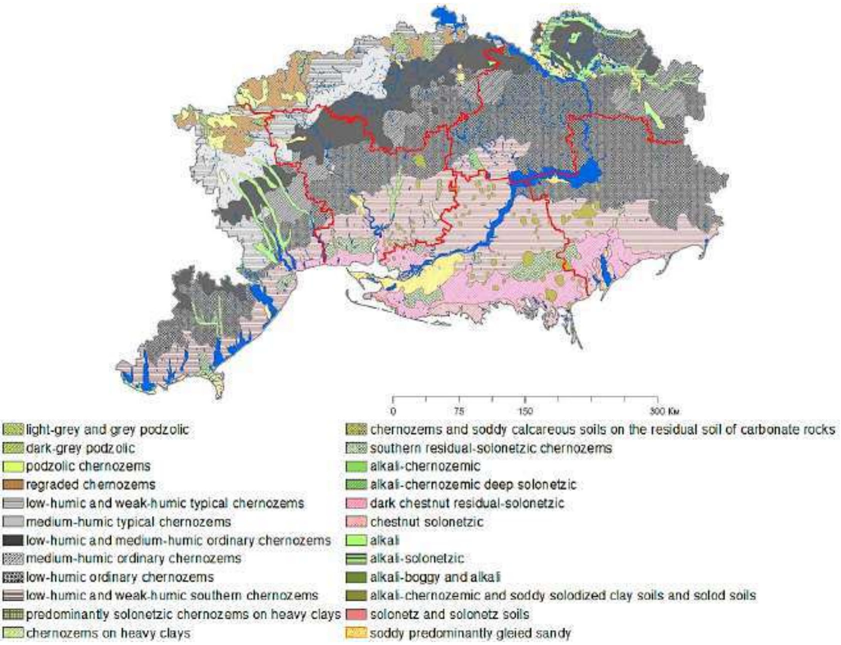


Figure 3. Types of soils in the studied steppe regions

$$C = \exp(-\alpha((NDVI)\,/\,(\beta - NDVI))), \tag{4}$$

where α and β are dimensionless parameters that determine the shape of the curve, which refers to NDVI and C factor. Parameters α and β have value 2 and 1, respectively. The coefficient of soil conservation measures (P) was takes as 1, suggesting that additional activities were not carried out.

The coefficient of soil protection measures (P) is equal to one, because additional anti-erosion measures throughout the study area are virtually absent.

To determine the potential soil loss in the territory of the steppe of Ukraine, the model of wind erosion carried out by NSC "Institute for Soil Science and Agrochemistry Research named after O. N. Sokolovsky", which was adapted to the different physical-geographical conditions of the country, was used (Mozheiko et al., 1980; Achasov et al., 2000; Bulyhin, 2005):

$$E_p = \frac{10^{a-bk} \times 0.1K_s \times V^3_{av\_\max} \times t \times K_{spe}}{V^3_{aer}}, \tag{5}$$

where E_p is the potential deflation soil loss, t/ha per year; a, b are the exponential coefficients depending on the genesis, granulometric composition, density and other soil properties (calculated experimentally); k is the clodding of the surface (0–3 cm) soil layer (content of aggregates or particles more than 1 mm), %; K_s is the destruction coefficient for aggregates of the surface soil layer under the influence of impacts of soil particles and their abrasion by an air-dust flow; $V^3_{av\_max}$ is the average maximum wind speed during dust storms of the 20th occurence, m/s (20% occurence shows that this indicator, which was determined according to multi-year data, is true in 80 cases out of 100, that is, only in 20% of cases the wind speed will be higher during dust storms); t is the average number of hours with the effect of wind erosion per year according to multi-year data; K_{spe} is the coefficient of soil protective effectiveness of anti-deflation activities; V_{aer} is the basic flow velocity in an aerodynamic plant, which is equal to 23 m/s in terms of the height of the wind vane (10 m); 0,1 is recalculation from g/m^2 for 5 minutes to t/ha per year.

Spatial models of the distribution of the magnitude of the regression coefficients (a, b), clodding (k) and destruction coefficient (K_s) have been created on the basis of assigning the corresponding values (Table 2) to each soil variety of the steppe zone of Ukraine (Fig. 3). Raster models of spatial distribution of the average maximum wind speed during dust storms (V_{av_max}), the average number of hours with the effect of wind erosion per year (t) in the territory of steppe soils have been obtained on the basis of extrapolation of decompositions of meteorological cartograms according to 47 meteorological stations in the period 1990–2018.

Table 2. Values of wind erosion calculation values for the main soils of Ukraine

Types of soils	Soils description	a	b	k	K_s
1	2	3	4	5	6
Sod-podzolic, sod podzolized, gleyed, podzolized sandy, clay-sandy and sandy-loam soils	These soils were formed under the conditions of excessive moisture under pine and mixed forests. Humus content in the arable layer of these soils is low and ranges from 0.7–1.0% in sandy and sandy-loam to 1.5–2.0% in loamy soils. They are tight (1.40–1.55 g/cm), store little moisture, have high water and air permeability, low absorption capacity and lack of nutrients, the soil solution in them is acidic – pH 4.2–5.2	2.3497	0.0339	15–20	0.75–0.9

Continuation of Table 2

1	2	3	4	5	6
Peat-bog soils and peatlands	These are soils with a large number of undecomposed and semi-decomposed plant residues (peat), which are accumulated in them under the impact of prolonged excessive moisture. The soils are mostly characterized by an alkaline reaction of the soil solution. The average pH values of an aqueous solution in the organogenic layer are 7.3–8.2, salt pH is from 7.0 to 7.5	6.1675	0.0918	43–66	0.9–1.0
Gray podzolized soils, podzolized and solonetzic chernozem soils, chestnut solonetzic soils, loamy and clay solonetz	*Gray podzolized soils* formed under forest vegetation. They occur on watershed plateaus. They have a clear differentiation of the profile by the eluvial-illuvial type. The reaction of the soil solution is acidic, fulvic acids predominate in the humus. The soils are depleted of nutrients, humus content is in the range of 1.5–2.7%. *Podzolized and solonetzic chernozems* contain 3.0–4.0% of humus in the arable layer, its amount gradually decreasing with depth. The availability of mobile forms of phosphorus and potassium is mostly average; it is low in the third of the soils.	3.0052	0.0252	48–52	0.3–0.7

Continuation of Table 2

1	2	3	4	5	6
	The reaction of the soil solution is slightly acidic, close to neutral (pH 5.6), so the soils need liming only in some cases. The thickness of the humus layer of *chestnut solonetzic* soils is 25–50 cm. They have a pronounced eluvial-illuvial differentiation of the profile. Humus content is 2.0–3.0%.				
Typical and ordinary not eroded and weakly eroded chernozems, meadow soils, meadow-chernozem soils, chernozem-meadow soils	These soils are characterized by high natural fertility with a high content of humus (4.0–5.0%), have a slightly acidic reaction of the soil solution (pH 5.7–6.4). The amount of absorbed elements ranges from 25.0 to 35.0 mg-eq. per 100 g of soil, and the degree of saturation of the elements reaches 90.1%. The humus horizon is 70 cm or more	3.4915	0.0351	29–46	0.5–0.6
Typical and ordinary medium- and highly eroded chernozem soils	By their granulometric composition, typical chernozems are mainly light loamy, less often they are heavy loamy. They have significant reserves of humus (4.0–5.0% in low-humus to 6.0–8.0% in medium-humus soils), high nutrient reserves. The content of mobile compounds of nutrients rarely changes depending on the level of agricultural technology, the degree of humidity, and other characteristics.	4.3060	0.0580	26–44	0.4–0.6

Continuation of Table 2

1	2	3	4	5	6
	The degree of mobile phosphorus supply is mainly medium, of potassium – high, medium and low, of nitrogen – medium and high. Due to relatively shallow deposits of calcium and magnesium carbonates, there is a neutral or slightly alkaline, close to neutral, reaction of the soil solution (pH of salt extract is 6.3) in the humus horizon of these soils. The hydrolytic acidity of deep chernozems is very low: on average, it is 1.3 mg-eq. in the arable layer, and 0.3–0.6 mg-eq. per 100 g of soil at a depth of 50–70 cm. The amount of absorbed elements is high – 30.1 mg-eq. per 100 g of soil in the humus horizon, the degree of saturation with the elements being 96%				
Southern chernozem soils of all types except solonetzic	These soils formed in the southern part of the Steppe zone. The humus horizon usually reaches 50–85 cm. Humus content in heavy-textured soils is 2.5–4.3%, in medium loamy soils, it is 2.0–3.0%	3.6955	0.03773	31	0.6
Southern solonetzic chernozem soils	These soils develop on clays, often saline, which causes the formation of the solonetrization process.	2.7830	0.0200	29–43	0.6–0.8

End of Table 2

1	2	3	4	5	6
	Compared to other chernozems, they contain less humus (2.0–2.5%) and have worse water-physical and physicochemical characteristics.				
Sandy-loam and clay-sandy chernozem soils	These soils have a light loamy and sandy texture with a humus content of 0.4–2.0%. The level of saturation with the elements is 75–80%. The characteristic of the profile is the same as in other chernozems	3.6627	0.0218	23–45	0.6–0.8
Chernozem soils on dense clays	Occurrence on dense clays leads up to unfavorable physical properties. Soil horizons are very dense, impervious, viscous when wet, difficult to cultivate, get flooded, form hard lumps after drying. These soils contain a significant amount of humus (6.3% in the arable layer), are characterized by low acidity in the humus horizon (salt pH is 6.2–6.4), a neutral reaction in the lower genetic horizons, low hydrolytic acidity and high values of absorbed elements (1.5–3.0 and 43.6–50.2 mg-eq per 100 g of soil, respectively). The saturation with the elements is close to absolute – 94.7–99.0%	3.4915	0.0351	27–42	0.6

The coefficient of soil-protective effectiveness of deflation resistance activities (K_{spe}) was calculated using the modified crop erosion index or the vegetation cover coefficient (C') according to the formula:

$$C' = C/\max(C)\ . \tag{6}$$

The value is calculated according to the formula 3. The value C' is within 0 (maximum anti-deflation effect of vegetation cover) and 1 (minumum or absent anti-deflation vegetation).

Methods for the second stage of research. The method of fertility of zonal soils according to Karmanov (1980, 2012, 2013) was adapted and tested in accordance with the uniform comparative scale for assessment of soil fertility to create spatial models of soil bonitet in the steppe of Ukraine. Both soil properties and the climate bonitet were included in this method considering main climatic indicators that are correlated with yield capacity, i.e. the amount of active temperatures, moisture ratio, continentality of climate. The methodology reflects the general regularities of spatial distribution of yielding capacity according to natural physical and geographical zones and allows to calculate the points of bonitet for crops according to the formula:

$$B = 8.2V\,\frac{\sum t^{\circ} \geq 10^{\circ} \times HF}{CC + 70}\ , \tag{7}$$

where B is a point of bonitet; V is the total index properties of soil; $\Sigma t^{\circ} \geq 10^{\circ}$ is the average annual temperatures above 10 °C; HF is the rainfall factor according to Ivanov (HF that is more than 0.9 is taken equal to 0.9); CC is the coefficient of continentality.

Having data about terrain, it is possible to extrapolate climatic characteristics for each local element of the landscape that will help to specify the conditions of the microclimate and, accordingly, to set the point of bonitet of soils.

Calculation of soil and climatic potential of soils and receiving raster models of its distribution should be implemented according to the formulas of calculation of bonitet points for zonal soils in the working module of Raster Calculator module of ArcGIS.

The value of the coefficient of continentality of the climate (*CC*) shall be calculated according to the formula:

$$CC = \frac{360(t^{o}_{\max} - t^{o}_{\min})}{\varphi + 10}, \tag{8}$$

where $t°_{\max}$ is the average monthly temperature of the warmest month; $t°_{\min}$ is the average temperature of the coldest month; ϕ is the latitude of location.

Coefficient of moisture (*HF*) shall be determined according to the formula:

$$HF = P / E, \tag{9}$$

where P is the average annual precipitation, mm; E is the annual evaporation, g/cm^2.

The summary indicator of soil for the territory of Ukraine properties shall be determined in accordance with coefficients of the total indicator of soil properties (*V*) from 0.5 to 0.98 (Table 3, see p. 20).

Spatial models of the sum of active temperatures, humidity and continentality of the climate, which are presented and described in the section results and discussion, were determined on the basis of extrapolation of decompositions of publicly available data CliWare (http://cliware.meteo.ru/meteo), additional data from individual weather stations and the national atlas.

To specify the assessment of the spatial differentiation of soil condition, the calculation of the points of bonitet included factor of complex negative impact of water and wind erosion, which determined the degree of degradation of soil and loss of crops.

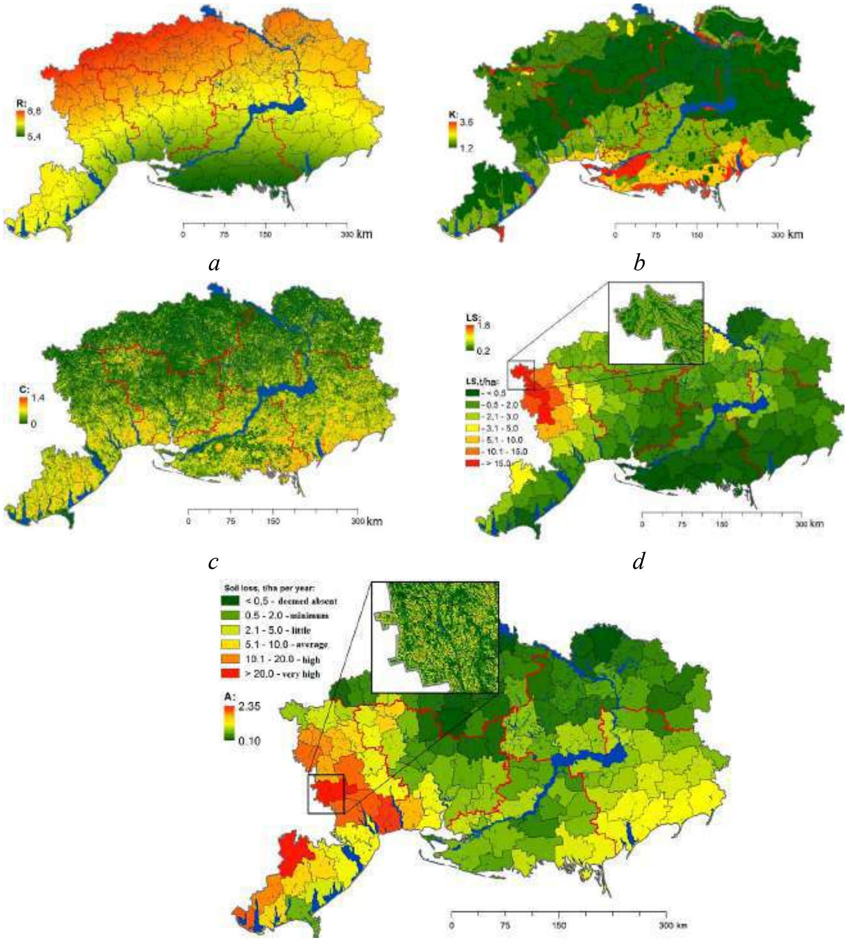
Modeling and analysis of the spatial distribution of the studied indicators of soil condition in the Steppe of Ukraine was carried out in the GIS environment licensed software for ArcGIS 10.1.

Table 3. Estimated values of the total indicator of soil properties (V)

Soils	*V*	Soils	*V*
Soddy-sand and chestnut-solonetzic soils	0.5	Meadow-chernozem:	
Podzols	0.67	forest-steppe zone	0.92
Sod-podzolic	0.73	steppe zone	0.96
Forest storms	0.81		
Light gray forest	0.78	Dark chestnut	0.86
Gray forest	0.81	Chestnuts	0.81
Dark gray forest	0.86	Light chestnut	0.78
Chernozems:		Meadow and chestnut	0.90
podzolic	0.92	Brown	0.85
leached	0.96	Gray-brown	0.88
typical	1.00	Gray soils	0.90
ordinary	0.96	Meadow-chernozem	0.85
southern	0.92	Sod-carbonate:	
		typical	0.92
		leached	0.90

RESULTS AND DISCUSSION

As a result of geomodelling, the spatial heterogeneity of the differentiation of the main factors of water erosion and degradation of soils in the Steppe zone of Ukraine was determined, i.e. the erosive potential of rainfall (*R*) uniformly increases from South to North-West from 5.4 to 8.8 (Fig. 4, *a*, see p. 21); potential annual loss of fertile top soil (*K*) (depending on the erosion potential of precipitation) decreases from north to south from 3.6 to 1.2 t/ha (Fig. 4, *b*, see p. 21); the values of erosion crop index (*C*) is within 0 and 1.4 in the direction from north to south (Fig. 4, *c*, see p. 21); the importance of the terrain factor (*LS*) varies from 0.2 to 1.8 (Fig. 4, *d*, see p. 21); agricultural land of northwestern area of steppe of Ukraine has the highest erosion hazard of terrain. As a result of GIS modeling using the modified RUSLE model, the erosion risk was assessed, the potential annual soil loss on arable land was calculated (Fig. 4, *e*, see p. 21). About 4,304.5 thousand ha of arable land was allocated. It has increased (more than 2 t/ha per year) erosion risk (32.7% of the total arable



a *b*

c *d*

e

Figure 4. Spatial distribution of total soil losses due to water erosion in the steppe zone of Ukraine:

a – is the rainfall erosion index (*R*); *b* – is the soil resistance (erodibility) to erosion, t/ha (*K*); *c* – is the erosion index for crop or crop rotation in general (*C*); *d* – is the topography factor (*LS*); *e* – is the spatial distribution of soil losses (t/ha per year) land). Conventionally erosion safe lands belong to the plains and the buffer borders of the watersheds of slopes and they take 67.3% of the total arable land, but they are subjected to water erosion (Dudiak et al., 2019).

It was determined that the increase in the amplitude of the temperature fluctuations of air and soil, reduction of the amount of the annual precipitation (Pichura et al., 2019), hydrothermal coefficient, reduction of the frost-free period, increased activity of the wind contribute to the development of deflation processes, which is determined by the influence of the erosion dangerous climate that is determined by continentality (Shahaev, 2004).

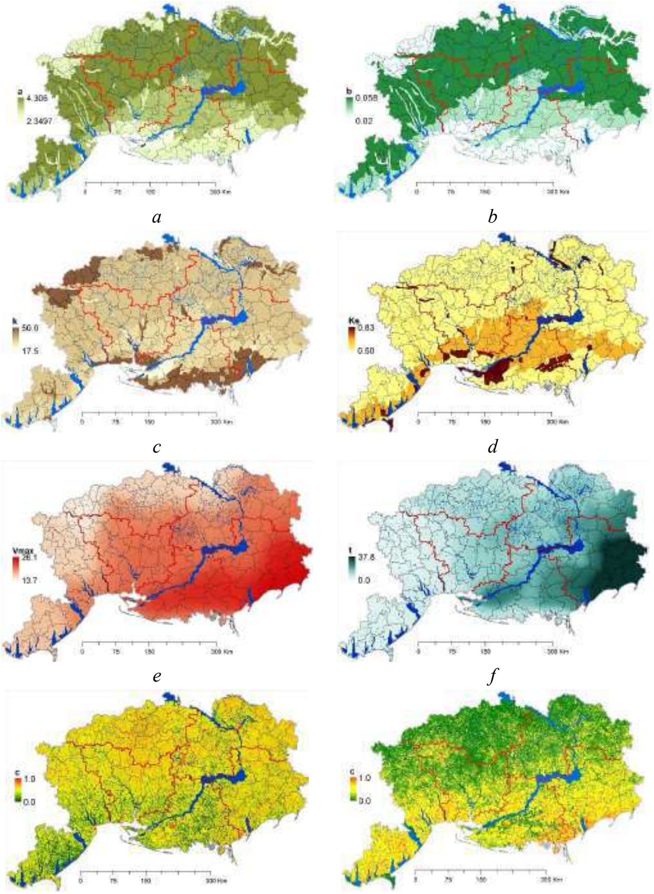
Wind erosion is significant for arid and semiarid areas that have little rainfall, high air temperature and degree of evaporation, enhanced by strong winds and low differentiation of plant protection. First and foremost, the area of wind erosion strengthening has soils in the steppe, which are characterized by light granulometric composition, low speed of soil formation, medium and low humus content, poor connectivity and strength of a soil clod. In the steppe, mainly flat terrain, the wind acquires a high velocity that implies an increase of the strike force of particle transfer.

Deflation destruction of the soil cover associated with the wind factors (speed, frequency of repetition, its force and duration); characteristics of the earth’s surface (vegetation, its height and density of cover, surface roughness, availability of soil moisture), soil specifics (size of sites, their connectivity, the distribution of units and amount of organic matter) (Bulyhin, 2005; Luo et al., 2019; Chi et al., 2019). As a result of wind erosion, 5–6 million hectares of fertile land are being annually damaged in open steppe landscapes. The most active and harmful form of wind erosion occurs in the steppe and partly forest-steppe zones when wind speeds are greater than 12–15 km/h. The research found that low efficiency of existing contour-meliorative anti-deflation activities in the Steppe zone of Ukraine caused a large-scale disaster of 2007, when about 20% of agricultural land was in the middle of dust storms. In this regard, soil loss ranged from 10 to 400 t/ha (Chornyi et al., 2007).

The spatial modeling resulted in creation of a raster model of spatial differentiation of wind erosion factors and calculations of deflation soil loss in an area of steppe of Ukraine. The coefficients of the regressions (*a*, *b*), clodding (*k*), coefficients of destruction (K_s) for major soils of Ukraine were calculated in accordance with the method of potential soil loss (Mozheiko et al., 1980; Achasov et al., 2000; Bulyhin, 2005). It was determined in the study that the coefficients of the characteristics of genesis, granulometric composition, density and other properties of soils of the steppe region vary factor-a (Fig. 5, *a*, see p. 24) from 2.3497 (sod-podzolic, sod podzolized, gleyed, podzolic sandy soils, clay-sandy and loamy soil) to 4.3060 (chernozem soils typical and common medium and highly eroded soils), factor-b (Fig. 5, *b*, see p. 24) from 0.020 (chernozems southern solonetzic soils) to 0.058 (chernozem typical and common medium and highly eroded soils).

The average value of the factor-k (Fig. 5, *c*, see p. 24) varies within 17.5% (sod-podzolic, sod podzoli zed, gleyed, podzolic sandy soils, clay-sandy and loamy soil) and 50.0% (gray podzolics, podzolic and alkaline chernozems, chestnut alkaline, alkaline loamy and clay soils), the factor-K_s (Fig. 5, *d*, see p. 24) varies within 0.5 (chernozem soils typical and common medium and highly eroded soils) and 0.83 (sod-podzolic, sod podzolized, gleyed, podzolic sandy soils, clay-sandy and loamy soil). Average maximum wind speed during dust storms of a 20% security (V_{av_max}) decrease from the south-eastern part to the north-eastern part of the studied region from 26.1 to 13.7 m/s (Fig. 5, *e*, see p. 24).

The average number of hours per year with dust storms (*t*) in the steppe zone of Ukraine also varies from 0 to 37.8 hours (Fig. 5, *f*, see p. 24) in this direction. Spatial differentiation the deflation impact of the factor-*C′* depends on the distribution of areas of land occupied by natural vegetation and agricultural crops. The seasonal value varies from 0 to 1 (Fig. 5, *g*, see p. 24). As a result of GIS modeling using the model of potential soil losses due to deflationy processes in areas taken by clean steam (in the absence of erosion control activities), soil losses in the middle of dust storms will range from 0.02 t/ha to 598.3 t/ha (Dudiak et al., 2020).



a *b*

c *d*

e *f*

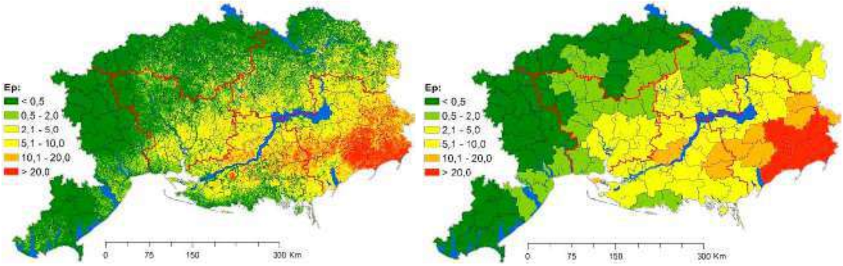
March *August*

g

Figure 5. Spatial distribution of factors of the deflation process in the steppe zone of Ukraine:

a, *b* – coefficients that depend on the genesis, granulometric composition, density and other soil properties; *c* – clodding of the surface soil layer, %; *d* – is the destruction coefficient of the aggregates of the surface soil layer; *e* – is the average maximum wind speed during dust storms of the 20th occurrence, m/s; *f* – is the average number of hours involving wind erosion effect per year; *g* – is the coefficient of deflation resistant efficiency of the crop or crop rotation

Potential soil losses are reduced 5.62 times under the conditions of the anti deflation efficiency of the crop or crop rotation of factor-*C′* comparing with the model of the absence of anti-deflation measures (Fig. 6, *a*).



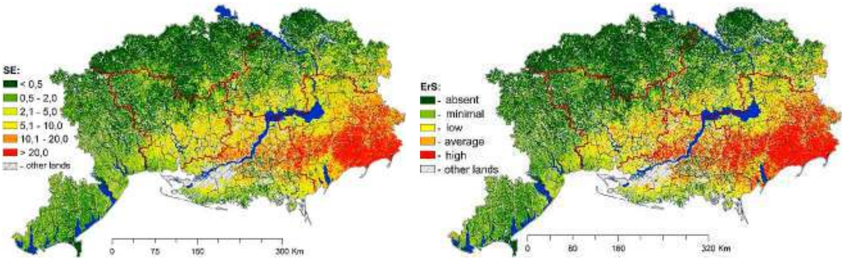
a *b*

Figure 6. Modeling the spatial distribution of potential deflation soil losses (t/ha per year) in the steppe zone of Ukraine:
a – is the spatial distribution cartogram; *b* – is the average value for administrative-territorial districts

It was determined that about 40% of agricultural land has a strong and very strong deflation processes. It is mainly located in the central and southeastern parts of the steppe zone of Ukraine (Fig. 6, *b*).

Based on raster models of soil loss (t/ha) due to water (Fig. 4, *e*) and wind (Fig. 6, *a*) erosion, the raster model of spatial differentiation of the total water and deflation destruction of steppe soils (Fig. 7, *a*, see p. 26) has been created. The distribution of agricultural land by gradation of erosion hazard is shown in the Table 4 (see p. 26).

Conditionally erosion-safe land (31.3% of total arable land) include the land of the plain and the buffer borders of watersheds of slopes that has vegetation (bio- and agrocenoses). About 68.7% of arable land are constantly influenced by the combined effect of erosion processes, in particular: minimum and low negative effects take place in 41.5% of the area, average effects in 11.6%, high and very high – in 15.6% of arable land.



a *b*

Figure 7. The spatial distribution of total soil loss (t/ha per year) due to water and deflation destruction of soils in the steppe of Ukraine: *a* – is the total destruction of soil (*SE*); *b* – is the degree of soil erodibility (*ErS*)

Table 4. Distribution of arable land according to potential hazard of water and deflation soil destruction

Erosion hazard	**Soil loss, t/ha per year**	**Degree of erosion development**	**Area, thous. ha**	**Percent area, %**
Conventionally absent	<0.5	I category	4,119.2	31.3
Minimum	0.5–2.0	II category	3,048.4	23.2
Low	2.1–5.0		2,404.5	18.3
Medium	5.1–10.0	III category	1,531.0	11.6
High	10.1–20.0	IV category	1,070.1	8.1
Very high	>20.0		988.9	7.5
Total:			13,162	100

It was determined that in the absence of environmentally justified erosion control measures the degradation processes of soil, which are charactarised by erodobility indicator, increased. In particular, lands that used to have category of weakly and low eroded became medium or highly eroded (Fig. 7, *b*) due to the loss of the most fertile layer of soil, removal of humus (dehumification of soil) and nutrients, significant deterioration of the physical properties of soils and, ultimately, a decrease in crop yields. With the deterioration of agrophysical properties of soil, its propensity to erosion, which can lead to complete loss of humus horizon and irreversible deterioration of the soil, increses.

It was determined that over the last 40 years the area of eroded lands in Ukraine has increased by 2.5 million ha. Thus, eroded lands annually extend for 60–80 thousand ha. During 1960–2015, the area of eroded soils increased by 30–35%; the area of highly washed out soils increased by 20%; low – and medium washed out soils increased by 2 and 12%, respectively (Baliuk et al., 2010). The area of low eroded arable land in the territory of the steppe of Ukraine is 2.2 million ha (16.8% of arable land), medium – and highly eroded land takes 2.9 mln ha (22.1%) (Table 5).

Table 5. Influence of the degree of erodibility of soils on change of their properties (the properties and indicators of uneroded soil are taken as unit)

Properties and indicators		**Erodibility of soil**				
		Absent	**Minimum**	**Low**	**Medium**	**High**
Agricultiral land	Thous. ha	4,844.3	3,202.8	2,210.0	1,316.4	1,588.6
	%	36.8	24.3	16.8	10.0	12.1
Humus content		1.0	1.00–0.95	0.95–0.75	0.75–0.50	0.50–0.30
Lightly hydrolyzed nitrogen		1.0	1.00–0.95	0.95–0.80	0.80–0.66	0.66–0.50
Mobile phosphorus		1.0	1.00–0.82	0.82–0.70	0.70–0.60	0.60–0.40
Exchangeable potassium		1.0	1.00–0.91	0.91–0.85	0.85–0.80	0.80–0.70
Bulk weight		1.0	1.00–1.03	1.03–1.05	1.05–1.10	1.10–1.23
Moisture of plant wilting		1.0	1.00–0.96	0.96–0.90	0.90–0.85	0.75–0.65
Porosity (according to Zaslavskyi)		1.0	1.00–0.95	0.94–0.90	0.90–0.80	0.80–0.75
Full moisture capacity (according to Zaslavskyi)		1.0	1.00–0.98	0.98–0.95	0.95–0.80	0.80–0.70
Average yielding capacity of crops:						
– grain		1.0	1.00–0.85	0.85–0.80	0.80–0.60	0.60–0.30
– herbage		1.0	1.00–0.95	0.95–0.90	0.90–0.70	0.65–0.45

Infiltration ability of soil decreases to 30% in medium and highly eroded land and washing out increases by 1.5–2.0 times, which leads to the accumulation of the products of erosive destruction of soils in reservoirs. These products include agricultural chemicals, nutrients, heavy metals, including radionuclides. As a result, the quality of surface waters significantly deteriorates, eutrophication of the waters is provoked, silting of small rivers takes place, which is the cause of disappearance thereof.

Increase in areas with eroded soils determines the degree of degradation of territorial ecosystems (units) and makes the necessity of implementation of appropriate erosion control and land improvement activities relevant. It is necessary to compensate the loss of humus as a result of erosion to restore the fertility of eroded soils. Therefore, it is necessary to make 3 times more organic matter than the value of humus that has been washed away, as no more than 25–30% of the volume of organic fertilizers and green manure are being humified (Barvinsky et al., 2015).

The organisational component of rational agricultural land use is the bonitation of zonal soils, which is a universal evaluation of fertility when comparing agroclimatic conditions, the establishment of the degree of intensity of agriculture for ensuring effective environmental friendly production with optimum use of the potential of soil. Bonitation characterizes the zonal characteristics of soils as media for favorable plant growth, which is shown in quantitative indicators of fertility – the points (from 0 to 100 points). The points can be calculated according to soil properties and climatic conditions. The main ones are the content of humus, humus layer, granulometric composition, macronutrient content, moisture content, sum of active temperatures and other. It is necessary to consider all causal relations, in particular, the influence of terrain, as the total integral function that defines the process of redistribution of heat and moisture in soil. It largerly determines the yield of crops.

Bonitation of soil is a logical continuation of the integrated studies of land and the state cadastral assessment of agricultural lands. In the sphere of land relations, it is the basis for establishing land tax, rates, mortgages and rents, starting price at auctions. It is also used in other areas related to land management, ecological-economic assessment of degradation of soil cover and reduction of agricultural crops according to the degree of erodibility of soils.

The main soil types of the regions in the steppe of Ukraine are chernozems. They take 83.2% of the total area of agricultural land, chestnut and dark-chestnut soil take 7.7%. Soil and climate bonitation is carried out on the basis of rasters of spatial distributions of four components of the bonitation of zonal soils: summary indicator of soil properties (V), the coefficient of moisture (HF), the coefficient of continentality of the climate (CC), average annual sum of active temperature above 10 °C.

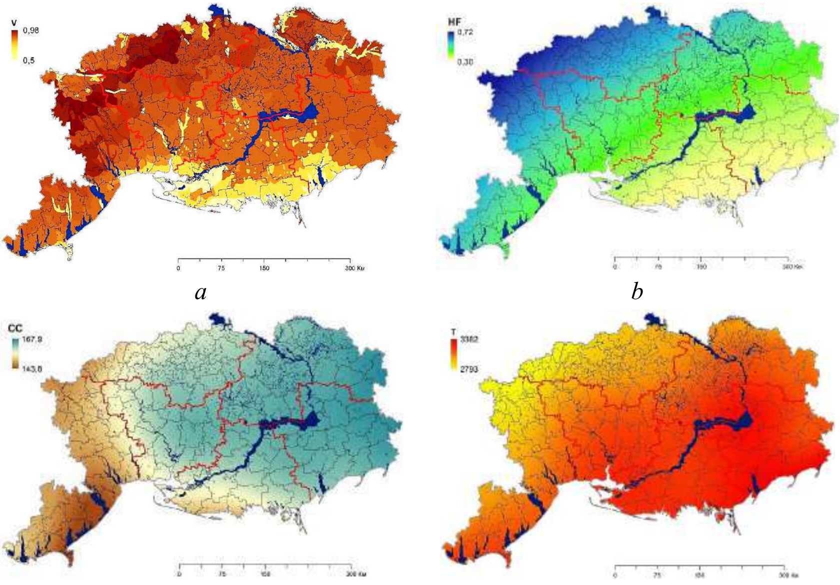
Depending on soil type, the spatial differentiation of the value of the total indicator of the properties of zonal soils (V) is from 0.5 for sod sandy and chestnut alkalinized soils to 0.98 for typical chernozem (Fig. 8, *a*, see p. 30).

Coefficient of moisture (HF) was calculated according to the method of Ivanov (1949) and it is calculated as the ratio of annual precipitation to annual value of evaporation for the relevant landscape, which is a ratio of heat and moisture (it helps to distinguish zones that provide biocoenosis with moisture). In the territory of the studied steppe region the value of HF decreases from north-west to south-east from 0.72 to 0.30 (Fig. 8, *b*, see p. 30). The reverse process is characterized by increased continentality of climate (CC). It characterizes the amplitude of the high air temperature, low rainfall and weak winds at high values. On the territory of the studied steppe region the value CC is within 143.8–167.9 (Fig. 8, *c*, see p. 30). Bioclimatic potential of agricultural production is largely associated with solar radiation, biochemical accumulation and migration of substances in soil, which are especially evident in the frost-free period when the air temperature is above 10 °C. Average annual sum of active temperatures in the studied area increases from north-west to south-east from 2,793 °C to 3,382 °C (Fig. 8, *d*, see p. 30).

As a result of the GIS modeling using soil and climatic models, Raster Calculator of ArcGIS 10.1 the points of bonitet of zonal soils for growing crops were calculated (Fig. 9, *a*, see p. 31). It was determined that under the existing soil and climatic conditions of the studied steppe region, the bonitet points for growing crops vary from 20.3 to 72.1 points (Dudiak et al., 2010).

Adjustment for the negative processes of water and deflation destruction of the soil cover with possible loss of grain crops was carried out (Fig. 9, *c*, see p. 31) to clarify the bonitet points (Fig. 9, *b*, see p. 31).

As a result of erodibility of the soil cover, a transition of about 23.3% of the agricultural land area from the category of high and medium quality to the category of medium, low and very low quality is observed (Table 6, see p. 32). It leads to loss of soil fertility up to 70%, a decrease in yield from 1 ha from 0.05 to 1.93 tonne (Fig. 9, *c*)

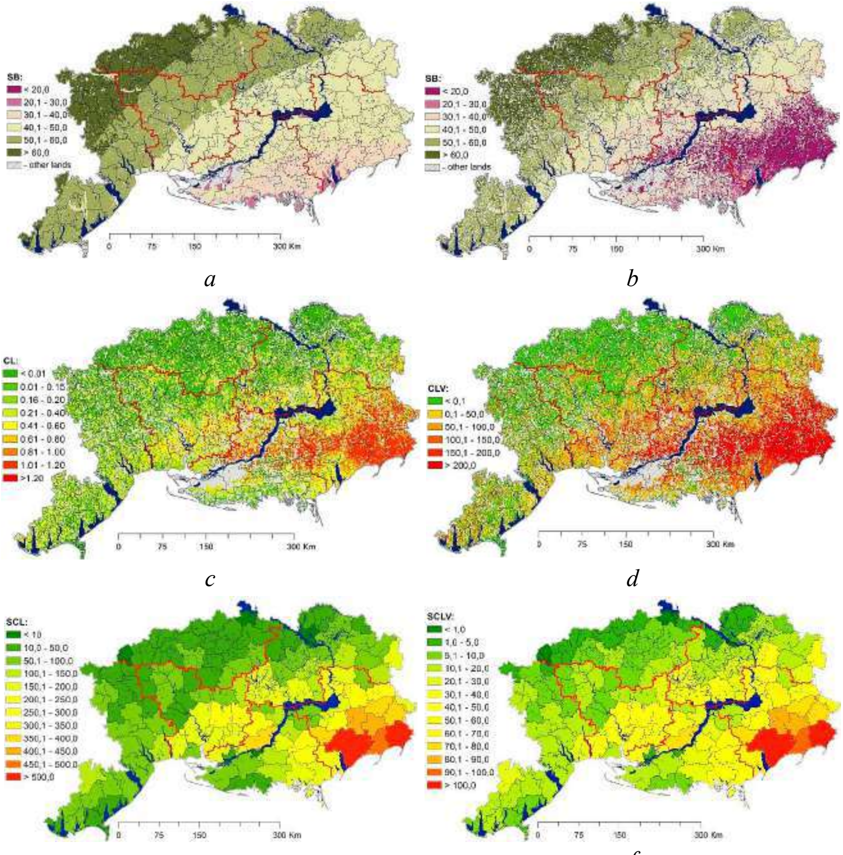


a *b*

c *d*

Figure 8. Spatial distribution of soil bonitation factors on the territory of the stupa zone of Ukraine:

a – is the summary indicator of soil properties (*V*); *b* – is the coefficient of moisture (*HF*); *c* – is the coefficient of continentality of the climate (*CC*); *d* – is the average annual sum of active temperature above 10 °C and, accordingly, a decrease in profit from 0.1 to 390 US dollars per 1 ha (Fig. 9, *d*). The total yield loss per individual administrative and territorial units is from 10 to 500 tonne or more (Fig. 9, *e*, see p. 31).



a *b*

c *d*

e *f*

Figure 9. Economic consequences of water and deflation destruction of soils of the steppe zone of Ukraine: bonitet of soil for growing of crops (*SB*):

a – excluding erosion destruction; *b* – including erosion destruction; *c* – spatial differentiation of wheat yield loss, centner/ha (*CL*); *d* – spatial differentiation of losses, dollars/ha (*CLV*); *e* – gross losses of wheat yield, tonne (*SCL*); *f* – total losses from crop loss, thousand dollars (*SCLV*)

It leads to agricultural losses of up to 100 thousand dollars and more (Fig. 9, *f*, see p. 31).

Distribution of the areas of the studied steppe region according to crop loss and a decrease in profit per 1 ha of agricultural land are shown in Table 7.

Table 6. Distribution of agricultural land areas according to soil and climatic potential and erosion destruction of soil

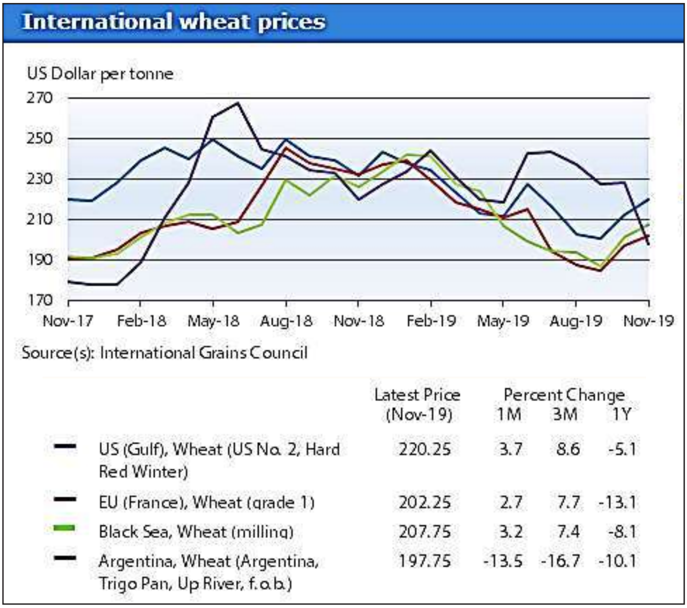
Soil quality	**Point of bonitet**	**Distribution excuding erosion destruction of soils**		**Distribution incuding erosion destruction of soils**		**Replcament, %**
		Area, thous. ha	**Specific weight, %**	**Area, thous. ha**	**Specific weight, %**	
Very low quality	10.1–20.0	—	—	1,488.7	11.3	+11.3
Low quality	20.1–30.0	181.9	1.4	965.8	7.3	+5.9
	30.1–40.0	1,531.6	11.6	2,326.6	17.7	+6.1
Medium quality	40.1–50.0	4,653.5	35.4	3,026.3	23.0	−12.4
	50.1–60.0	4,744.5	36.0	3,732.5	28.4	−7.4
High quality	>60.0	2,050.5	15.6	1,622.1	12.3	−3.3
Total:		13,162	100	13,162	100	—

Table 7. Distribution of agricultural land according to yield loss and material losses

Distribution of yiels loss					
t/ha	**Area, thous. ha**	**Percent area, %**	**dollars/ha**	**Area, thous. ha**	**Percent area, %**
<0.01	4,932.2	37.5	<0.1	4,932.2	37.5
0.01–0.15	213.2	1.6	0.1–50.0	3,150.1	23.9
0.16–0.20	1,678.2	12.8	50.1–100.0	1,952.0	14.8
0.21–0.40	2,148.5	16.3	100.1–150.0	1,346.4	10.2
0.41–0.60	1,586.2	12.1	150.1–200.0	311.6	2.4
0.61–0.80	924.6	7.0	>200.0	1,469.7	11.2
0.81–1.00	232.9	1.8	Total:	1,3162	100
1.01–1.20	1,245.3	9.5			
>1.20	200.9	1.5			
Total:	13,162	100			

The spatial differentiation of wheat yield losses in monetary terms was determined according to the data of Food and Agriculture Organization of the United Nations regarding export value of 1 tonne of grain for the countries of the European Union as of November 2019, which was $202.25 (Fig. 10) (http://www.fao.org/giews/food-prices/international-prices/detail/ru/c/1256179).

It was determined that the total yield loss due to water and deflation destruction of agricultural lands in the steppe zone of Ukraine is about 15.11 thousand tonne in the amount of 3,05 million USD.



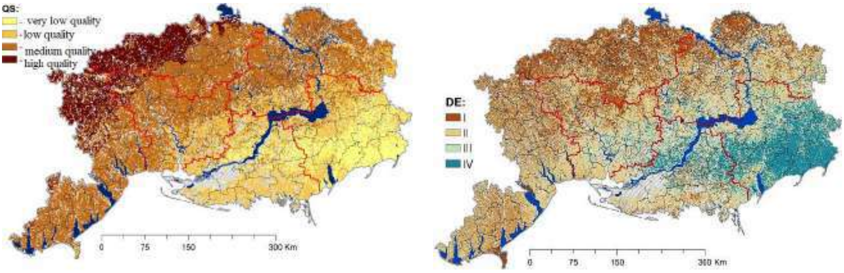
Source(s): International Grains Council

		Latest Price (Nov-19)	Percent Change 1M	3M	1Y
▬	US (Gulf), Wheat (US No. 2, Hard Red Winter)	220.25	3.7	8.6	-5.1
▬	EU (France), Wheat (grade 1)	202.25	2.7	7.7	-13.1
🟩	Black Sea, Wheat (milling)	207.75	3.2	7.4	-8.1
▬	Argentina, Wheat (Argentina, Trigo Pan, Up River, f.o.b.)	197.75	-13.5	-16.7	-10.1

Figure 10. The dynamics of changes in the export value of 1 ton of grain on the world market in 2017–2019

The environmental and economic assessment of damage due to soil erosion is characterized by quantitative indicators, in particular: the area of deflation lands washed out and destroyed by ravines; layer thickness, volume and mass of lost soil; applied micro elements (humus, nitrogen, phosphorus and potassium) into soil; amount of organic and mineral fertilizers for the restoration of eroded soils, increase of agricultural crops in the sowing due to their partial washing off and blowing off, increase in the resources for cultivating of eroded lands due to increase in the soil resistivity and short rutting, cost of gross output of crop shortages from eroded lands, increase in direct costs for the elimination of the consequences of erosion, structure of direct costs for land improvement of eroded lands and financing direct salaries and other costs (Lisetskii et al., 2012; Dudiak et al., 2019, 2020).

In order to protect soils from degradation processes, increase their fertility and crop yields in the steppe zone of Ukraine, it is necessary to implement activities of adaptive and landscape erosion control design with elements of soil-protective agriculture taking into account the spatial differentiation of soil quality for growing crops (Fig. 11, *a*) and categories of effects of erosion hazard of degradation of soil (Fig. 11, *b*).



a *b*

Figure 11. Spatial differentiation of soil quality (a – *QS*) and its category of erosion hazard (*b* – *DE*)

Soils of high quality take 12.3% of arable land. They are well provided with food compounds, have favorable physical, chemical and agrophysical properties. They lower the quality of land, poorly show negative properties of soils, take plains and slightly sloping slopes, are suitable for mechanized cultivation, provide stable harvest of zoned agricultural crops. Agricultural land of average quality prevails in the territory of studied steppe region. It takes 51.4% of the arable land area. It is characterized by the average supply of food compounds and productive moisture. It shows negative properties of soils (weak and average degree of acidity, alkalinity, etc.) and technological properties of land (division with network of beams, absence of shelter belts and buffer strips of natural vegetation, degree of erosion, etc.). Soils of low quality take 25.0% and they have a low supply of food components, insufficient reaction of the soil solution, water, air and thermal regimes, medium and highly negative properties of soils, technological peculiarities of land plots due to a significant tendency to erosion, limited suitability for growing crops. They require systematic use of high doses of fertilizers, land improvement and erosion control activities. Low quality soils take 11.3% of arable lands. They are characterized by low productivity with very low availability of food components, poor water and air and thermal regimes, have clear negative properties. They are also affected by significant erosion processes, are located on steep slopes, unsafe natural vegetation and forest belts, and are unsuitable for mechanical processing. Here, satisfactory yields are possible with application of high doses of fertilizers. It is necessary to provide integrated land improvement activities and implement adaptive-landscape erosion control activity in the territory including elements of conservation farming.

According to the intensity of influence of water and deflation destruction of soil, agricultural lands in the steppe of Ukraine can be divided into IV categories of erosion hazard (Fig. 11, *b*), according to which it is necessary to implement the activities of adaptive and landscape erosion control design including elements of conservation farming: I category covers land that are affected by erosion processes, soil loss is conditional (no less than 0.5 t/ha); II category covers lands with minimal and low erosion, soil loss of 0.5–5.0 t/ha; III category covers land with an average risk of erosion effect, soil loss is 5.1–10.0 t/ha; IV category covers land that is affected by high and very high erosion, soil loss is 10.1–20.0 t/ha or more. For I category of agricultural land with specific area 31.3%, it is recommended the use the zonal agricultural activities including preservation and restoration of shelter belts; for II category of 41.5%, it is recommended to apply simple erosion control activities, i.e. optimal timing of tillage, fertilizing, snow retention, nonmoldboard cultivation and planting with preservation of the stubble on the soil surface, location of crop and convertible husbandry in strips of width 100–200 m and perpendicular to the direction of wind erosion threat, additional establishment of shelter belts; for III category of land with specific area 11.6%, the same activities should be performed as for the land of II category including additional nonmoldboard cultivation and sowing with maximum preservation of stubble, creating belts of tall crops, band placement of crops and convertible husbandry in combination with buffer strips of perennial grasses, establishment of a system of shelter belts; for IV category of land with area 15.6%, it is recommended to apply the entire complex of erosion control activities, including introduction of soil-protective crop rotations with dominating perennial grasses in the crop rotation, nonmoldboard cultivation and sowing with maximum preservation of stubble on the soil surface, complete grassing of slopes against wind, application of crops, convertible husbandry and buffer strips with perennial grasses in strips of width of 50–100 m perpendicular to the direction of wind erosion threat, creation of a dense network of forest belts.

For the formation of environmentally sustainable agricultural landscapes and decrease of erosion and cumulative processes in the zone of steppe of Ukraine it is necessary to carry out the spatial differentiation of scientifically based systems of organizational-economic, agro-technical, forest improvement, hydro technical and melioration activities that are aimed at rational use of land resources, preservation and raising of soil fertility, reproduction of productivity for better use of all biological possibilities of territorial and aquatic ecosystems.

CONCLUSIONS

The spatial differentiation of environmental and economic effects of water and deflation destruction of steppe soil of Ukraine was carried out using GIS and remote sensing technology.

It was found that about 68.7% (8,818.5 thous. ha) of arable land is constantly affected by the combined action of erosion, the area of low eroded arable land is 16.8%, medium and highly eroded land is 22.1%. Due erodibility of soil cover, about 23.3% of agricultural land transferred from the category of high and medium quality to the category of medium, low and very low quality, which is caused by the loss of soil fertility up to 70%, reducing the yield from 1 ha from 0.05 to 1.93 tonne. The profit of agricultural producers decreased to 390 USD per ha. Direct costs increased due to use of eroded lands and violation of food security in the regions of the steppe Ukraine. Gross yield losses in administrative and territorial units vary from 10 to 500 tonne and more, which is the cause of loss in the amount of 100 thous. USD. It was established that the total loss of crops due to water and deflation destruction of agricultural lands in the steppe zone of Ukraine is about 15.11 thousand tonne for the amount of 3.05 million USD. To protect soils, increase fertility and productivity of agricultural crops in the steppe zone of Ukraine, it is suggested to apply adaptive and landscape erosion control design with elements of conservation agriculture.

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ECOLOGICAL AND ECONOMIC ASPECTS OF AFFORESTATION IN UKRAINE IN THE CONTEXT OF SUSTAINABLE LAND USE

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INTRODUCTION

In European countries until the middle of the XIX century forests occupied about 70–80% of the territory, during the period of agriculture evolution their area decreased by 15%. Nowadays, the forest cover of the territories of the developed countries ranges from 18% to 34.4%. Over the last half-century, the total forest area has significantly decreased, and developing countries have suffered the greatest losses. Taking into account the existing patterns of population base and the level of plowed up territories, the world forest reserve is expected to decrease by 32.1% per person in the next 30 years (State of the World…, 2000). The state of forest ecosystems is determined by the direct influence of man-made factors, which is expressed by the reduction of forest plantings as a result of logging, construction, creation of reservoirs, open mining, fires, etc. In economically-developed forests, natural forest growth conditions are disturbed, all components and relations of landscapes change, temperature changes, relative humidity decreases, wind speed increases, nature conservation capacity of forest plantings decreases, biomass and related thereto reproduction of energy resources reduces by 25–30%.

Domestic scientists (Shvydenko et al., 2018) have proposed a systematic assessment of the vulnerability of Ukrainian forests to climate change (Lisetskiy et al., 2018; Pichura et al., 2019) on the basis of scenario analysis and modeling of the dynamics of forest climatic resources. Forests, forming a part of the natural sphere of territorial ecosystems, perform a number of the most important, unique environmental, economic and social functions.

They influence the water exchange and state of aquatic ecosystems (Kalinin, 1950; Voronkov, 1973; Pichura, 2016, 2018), prevent water and wind erosion of soils (Pobedinsky, 1979; Buryak, 2015; Lisetskii et al., 2014; Dudiak et al., 2019), prevent the formation of gullies and landslides, fix sand landscapes and regulate the level of groundwater (Pichura et al., 2014), preserve landscapes, fulfill the multifunctional role in improving the environment (Gensiruk, 2002; Petrovich, 2014), contribute to obtaining guaranteed yields of agricultural products, and to increasing soil fertility (Lukisha, 2013). The degree of afforestation of territorial ecosystems ensures the preservation of their natural ecological balance, which is significantly impaired by human economic activities. Given the existing conditions of high anthropogenic load, it is necessary to search for the optimal interaction between man and nature to ensure balanced relations in the rational exploitation of the natural resources of the territorial ecosystems, with the aim of protection and target oriented restoration.

The objective of study is to investigate the current state and determine the environmental and economic aspects of afforestation in Ukraine in terms of sustainable land management, to propose the main ways of their solution.

MATERIALS AND METHODS

In the course of study we have used the data from the State Statistics Service and the State Service of Ukraine for Food Safety and Consumer Protection for the years 2008–2017. Interpretation of the data of remote sensing of the Earth and use of a series of correctly calibrated satellite images *MODIS* (geometric resolution 230×230 m) provided an opportunity to determine the ratio of the spatial distribution of the total forest area and the level of plowed up territories of agricultural land in the territory of Ukraine. A source of up-to-date satellite images data from various satellites is available on the official website of the US Geological Survey (https://earthexplorer.usgs.gov/). Spatial differentiation of the percent of plowed up agricultural land was performed on the basis of a series of satellite images *MODIS MODIS* as of 23.04.2016 and 13.08.2016.

Interpretation of images was performed on the basis of the values of the dimensionless index *NDVI* (normalized differential vegetation index) values within 0.3–0.4. The high degree of correlation of *NDVI* values of satellite images with the aboveground vegetation phytomass during the peak of their vegetative activity (June month) made it possible to determinate the spatial differentiation of the areas of forests and forest belts by maximum NDVI values – above 0.8. An additional specification of the spatial distribution of coniferous forests was made on the basis of the satellite images made in the winter period with *NDVI* values above 0.6. With the use of the Zonal Statistics of Spatial Analyst Tools module and the *ArcGIS* program, the forest cover and the percent of plowed up land within separate administrative-territorial units were determined.

RESULTS AND DISCUSSION

Ukraine belongs to sparsely forested and forest deficient countries. The forests in the territory of Ukraine are unevenly distributed, they are concentrated mainly in Polissia and Ukrainian Carpathians. In the period 1880–1924, 2 million hectares of Ukrainian forests were destroyed; the forest cover reduced by 5% during this period. The current total area of forest plots belonging to the forest fund of Ukraine is 10.4 million hectares, and the area of plots with forest vegetation is 9.6 million hectares. 79% of the forest area (including 73% of those of the State Forest Agency) is in permanent state use, 7% of the forest fund of Ukraine is in non-permanent use, 13% is subordinated to local self-government bodies, 1% is privately owned. The forest fund includes forest plots, including protective plantings of linear type with an area of at least 0.1 hectares. In general, Ukraine's forest cover with an optimum value of 25–30% is 15.9%, and in most steppe regions this figure does not exceed 1.9–4.8%. Ukraine ranks 9th among European countries in terms of forest cover. Forest cover in different natural areas has significant differences (Fig. 1, see p. 45) and does not reach the optimum level in terms of provision of important social, economic, environmental, landscape-stabilizing and raw material functions. The most wooded regions are: Zakarpattia, Ivano-Frankivsk, Rivne, Zhytomyr, Volyn and Chernivtsi regions. Zaporizhzhya, Mykolaiv and Kherson regions have the lowest indices.

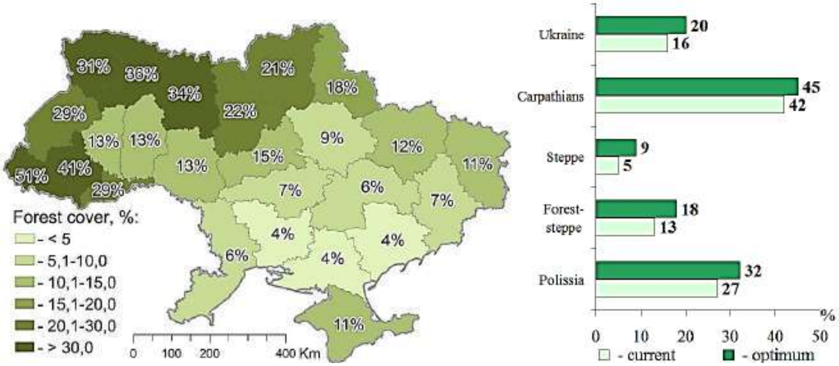

Figure 1. Spatial differentiation of forest cover of the territory of Ukraine

In addition to economic importance, forests perform the functions of soil and water protection against pollution and degradation, oxygen release and carbon sequestration, which promotes crop yields, preserves landscape and biological diversity, creates environmentally friendly living conditions, etc. About 3.5 million hectares of forests have restrictions on forest management, notably, this is the territory that was exposed to radiation contamination as a result of the Chernobyl accident (1986). According to the data of the State Statistics Service, 4.03 million hectares of forests were cut down in Ukraine in 2008–2017 (Table 1, see p. 46), about 170.7 thousand hectares were destroyed by fires, pests, storms and poachers, and only 16.3% of this area was restored.

As of 1 January 2019, the total area of dried forests was 440 thousand hectares, of which scots pine – 55.2%, common oak – 24.3%, European spruce – 5.9%, and other plantings – 14.6%. About 530 thousand hectares (13.15%) of plantings were restored during this period. In 2018, the total volume of illegal logging was 17.7 thousand m^3, and the amount of damage was 4.37 million USD, fire damage reaches 1.02 million USD. According to official data of the State Forestry Agency, in 2018, the industry enterprises harvested 16.5 million m^3 of timber, of which 32.0% was exported for a total amount of 14.98 million USD. According to the results of economic and financial activity of the enterprises of the forest industry in 2018, 629.2 million of net income was received from the sale of products (goods, works, services) of which about 417.98 million USD of net income was received by the industry enterprises. Ukraine ranks 34th in Europe in forest area-to-the total territory ratio. The average figure of the forest area which accounts for 1 person in Ukraine is 14 times less than in Eastern Europe. By total wood stock index (2.1 billion m^3) Ukraine ranks 6th among European countries.

Table 1. Characteristics of the change of forest areas in Ukraine

Years	**Area of logging, thousand ha**	**Destroyed, thousand ha**			**Restoration and creation of new forests, thousand ha**		**Protected from pests, thousand ha**
		by fire	**by insect pests and storms**	**for other reasons**	**total**	**incl. by enterprises of the State Forest Agency**	
2008	425	5.5	NA	NA	78.1	66.9	NA
2009	358	6.3	NA	NA	80.7	69.7	NA
2010	402	3.1	17.0	0.7	70.1	60.8	81.9
2011	422	0.9	14.5	1.0	72.4	61.5	141.2
2012	417	2.9	16.4	1.0	70.1	57.6	89.7
2013	415	0.3	15.5	0.7	67.7	55.4	99.6
2014	383	2.3	13.8	1.5	58.0	50.0	31.8
2015	399	8.6	16.8	2.4	60.4	51.0	46.0
2016	386	1.6	16.3	1.5	63.2	52.6	37.2
2017	419	8.8	10.8	0.5	64.7	53.8	46.1
Total	4,026	40.3	121.1	9.3	685.4	579.3	573.5

It has been determined that Ukraine's forests may produce about 160 million tons of organic matter per year, remove more than 290 million tons of carbon dioxide from the atmosphere and emit 210 million tons of oxygen. Over the period of 1 year the forest yield in Ukraine is 35 million m^3 of wood. The average annual change of stock per 1 hectare in the forests of the State Forestry Agency is 3.9 m^3 with its spatial differentiation from 5.0 m^3 (Carpathians) up to 2.5 m^3 (Steppe zone). In order to achieve the optimum indices of the forest cover, it is necessary to differentially restore the size of forest area in Ukraine by 6.0–9.2 million hectares. Based on the Letter of Appeal (No. 03-2057 dd. 10.11.2016) of the Accounting Chamber of Ukraine to the Chairman of the Verkhovna Rada of Ukraine regarding the results of the audit of the effectiveness of the use of budgetary funds for forestry and hunting sector, protection and defense of forests in the Forest fund and management of objects of public ownership, a number of violations and deficiencies in the forest management of Ukraine was revealed. This is due to a significant decrease in the financial support in the implementation of the relevant forest improvement measures, the lack of documentation of the state forest inventory; reduction in the annual volume of forest restoration (by 31.2% in 2011–2015), which reduced the area of forest creation in new territories from 22.4 thousand hectares (in 2011) to 2.4 thousand hectares (in 2015); an increase by 2.2 million m^3 in the volume of timber harvesting compared to 2011. The reduction in effectiveness of the economic activity of the state enterprises of the forestry sector is due to the low performance of the Unified State Electronic Wood Accounting System in Ukraine, which was confirmed by the fall in profitability from 7.8% to 4.7%. In the first half of 2016 compared to 2015. Today situation is complicated by the lack of proposals for sustainable development of the forest improvement industry in Ukraine, and the measures presented in the Strategy for Sustainable Development and Institutional Reform of the Forestry and Hunting Sector of Ukraine for the period until 2022 have a declarative character without clear deadlines and a situational forecast of the consequences of their implementation.

In Ukraine, the vast majority of forest belts were laid in the 50's and 60's of the XX century, and about 800 thousand hectares of field-protective forest belts – in the current period (Godovany, 2013.). Since 2000, field-protective forest belts have been subordinated to local councils, some of the field-protective forest belts have been managed by the State Forest Resources Agency, the Ministry of Agrarian Policy and Food.

The complication of the situation in Ukraine, in which the state of forest ecosystems does not meet the environmental and economic requirements, is caused by the complexity of management decisions in the field of forestry, which is caused by a long period of growing forests and the complexity of forecasting future options for the development of environmental and economic situations, which requires state financial support, development and rigid implementation of an environmentally balanced system of forestry management of the country, taking into account zonal requirements and norms of rational forest management.

The lack of a regulatory framework for regulation of the issues of preservation and restoration of field-protective forest belts causes their partial or complete destruction, which leads to a significant reduction of the nature preservation function of forest planting and large-scale manifestations of water and wind erosion, which lead to the process of loss and weathering of the topsoil and its nonuniform spatial redistribution, which causes degradation of soils, fertility fall, which leads to under-harvesting of crops. Wind erosion in the territory of Ukraine annually extends over 6 million hectares, and in the years of drought and dust storms – up to 20 million hectares. In March 2007, zonal manifestations of storms covered more than 12 million hectares of farmland, which lasted from 10 to 30 hours with an average wind speed of 15–20 m/s. According to the calculations of scientists (Chorny S. G. et al., 2007), soil losses in the epicenter of a dust storm from a surface without vegetation amounted to 150–400 t/ha, and in another area – to 10–50 t/ha, which is 10–4,000 times higher than the speed of modern soil formation. In the territory of Ukraine, as a result of erosion processes, agriculture loses from 10 to 12 million tons of grain per year.

The negative anthropogenically-induced influence on the condition of forest ecosystems and their restoration is exacerbated by manifestations in climate change. As a result of lookback study and modeling of climate changes, domestic scientists (Shvydenko et al., 2018) have determined the spatiotemporal patterns of inhomogeneity of changes in the conditions of growth of common oak in terms of humidity in the period 1960–2100 (Fig. 2, see p. 49).

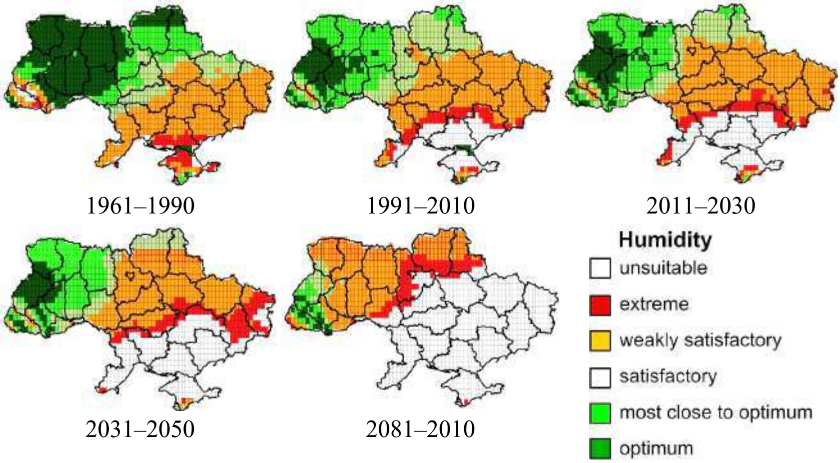

Figure 2. Spatio-temporal pattern of the change of climate conditions of the favorable growth of ordinary oak by humidity index in 1960–2100

It is established that by 2,100 more than 55% of the territory of Ukraine (the steppe and forest-steppe zones) will have unsuitable climatic conditions for the restoration of the common oak. Scientists have noted that climate change will lead to a shift in the forest distribution boundaries, replacement of zonal vegetation types, changes in the forest formations-to-forest types ratio; reduction of the viability of forests, their resistance to pests and diseases, increase in the intensity of forest drying; mass pest outbreaks; increase in the number and scale of fires (especially in coniferous forests); reduction of carbon deposits; decrease in productivity and marketability of forest stands; changes in the species composition of forests; reduction of the level of biodiversity, especially of species with a small climatic range (stenotope) and species on the border of ranges and endemic species.

During 1950–1990, 440 thousand hectares of field-protective forest belts were planted in Ukraine, of which 350 thousand hectares have field-protective and 90 thousand hectares – water-regulating purpose. They provided protection for 13 million hectares of agricultural land, as 1 hectare of forest belt protects 20–30 hectares of arable land, which increases crops yields by 15–20% compared to unprotected field plots. In areas of forest belts, the agrochemical properties of the soil improve, the speed of erosion processes (wind, water) decreases. In particular, in the field-protected forest belts the speed of wind decreases by 20–30%, microclimatic conditions also improve (in protected lands 80% of moisture penetrates into the soil, unproductive evaporation of moisture is reduced twice, surface temperature of the air increases by 1…3 °C the and relative humidity – by 3–5%). In addition, the protection of agricultural land from pollution by road transport emissions is increasing. Thus, favorable conditions for environmentally stable agriculture and formation of environmental and economic land management are being created (Lukisha, 2013; Openko et al., 2014). It is proved that for every unit of resources invested in the forest improvement, agriculture receives 1.5–2.0 times more of gross output than as a result of capital investment.

Thus, protective forest belts form the basis of land and forest improvement (Table 2), reducing the negative influence of the natural man-made factors on the change in soil fertility and contributing to the yield of additional crops. However, the average field-protective forest cover in individual physical-geographical areas

Table 2. Agroecological services of protective forest belts

Indices	**Territory**	
	unprotected	**protected by forest plantings**
Water reserves in the snow, mm	70–80	110–120
Flow of water into the soil, mm	58–63	100–108
Surface runoff, mm	19–20	6–7
Soil loss, m^3/ha	3.0–4.0	0.5–0.7
Total evaporation of moisture during the growing season, mm	750–760	625–640
Relative humidity at 13:00 in July, %	25–28	30–34
Relative humidity in dry years, %	14–15	20–22
Total number of animal species	35–60	83–149
Zoomass per 100 ha of territory, kg	180–186	358–880

of Ukraine varies within 1.3–1.5%, with the required optimum level of 3–4.5% (Pylypenko et al., 1998; Stadnik, 2012).

According to official statistics, as of 01.01.2017 about 446 thousand hectares of field-protective forest belts were recorded in Ukraine (Fig. 3).

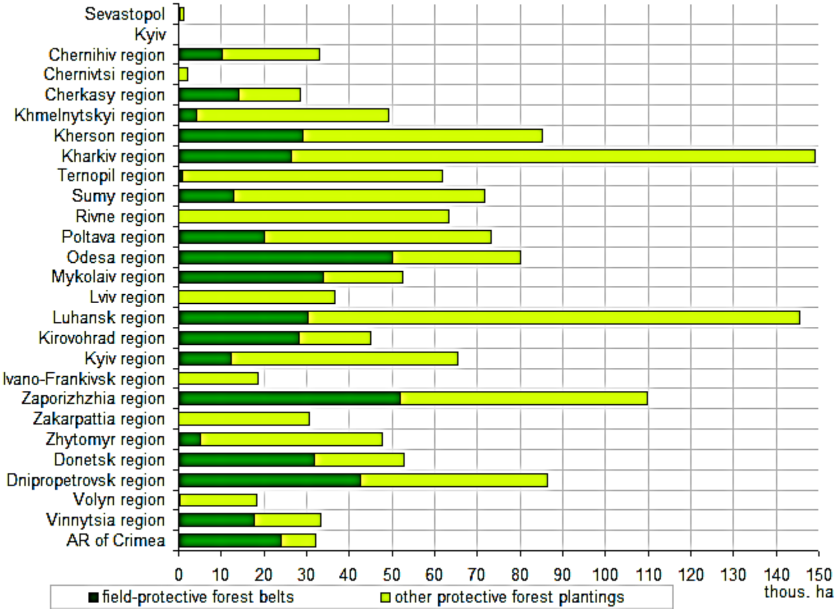

Figure 3. Distribution of protective forest plantings areas in Ukraine

According to data from the State Service of Ukraine for Geodesy, Cartography and Cadastre, as of 01.07.2016 (In Ukraine, the field-protecting forest strips..., 2016), significant deviations of the actual areas of protective forest belts from the land explication determined in the projects of denationalisation and land privatization of agricultural enterprises (1995–1997) were detected in 12 regions. It was established that the total losses amount to 10,071 hectares (Fig. 4, see p. 52), with the greatest losses of protective forest belts in the Southern regions of Ukraine, in particular, in Kherson (32.5% of the area of total losses), Zaporizhzhia (22.5%), Mykolaiv (16.4%), Odessa (16.3%) and Kirovohrad (9.5%) regions.

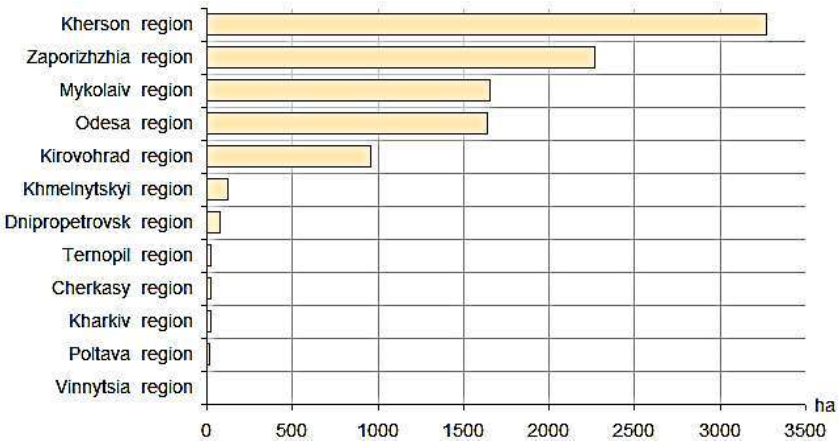

Figure 4. Areas of destruction of protective forest belts in the territory of Ukraine for 1995–2016

Therefore, based on the obtained results of study, the area of field-protective belts has been reduced by 1.9–2.3 times over the last 60 years. The actual area of the protective forest belts is 350 thousand hectares, based on the standard indices additional 700 thousand hectares require restoration too. The uncertainty of the ownership of field-protective belts in the course of land reform complicates and slows down the process of their restoration.

It is established that the forest cover of the Steppe zone of Ukraine (Fig. 5) in 130 administrative-territorial units (Dnipropetrovsk, Zaporizhzhia, Kirovohrad, Mykolaiv, Odesa, Kherson regions, with the total study area of 167.4 thousand km^2) varies from 0 to 27%: about 36.8% of the territory of the 46 administrative-territorial units (ATU) has a forest cover of less than 1.0%; 31.5% of the territory has from 1.0 to 3.0% of the forest cover (40 ATU); the forest cover of 14.9% of the territory is within the limits of 3.1–5.0% (18 ATU); the forest cover of 7.9% of the territory is within the limits of 5.1–10.0% (13 ATU);

the forest cover of 5.4% of the territory is within the limits of 10.1–15.0% (7 ATU); the forest cover of 3.6% of the territory is more than 15% (6 ATU). About 76.0% of the territory of the Steppe zone of Ukraine is characterized by insufficient forest cover, which causes systematic negative manifestations of water and wind erosion. This situation is complicated by the high level of agricultural development of the southern regions – up to 97% (Fig. 6, see p. 54), which causes a low degree of environmental sustainability of landscapes to preservation of soil fertility.

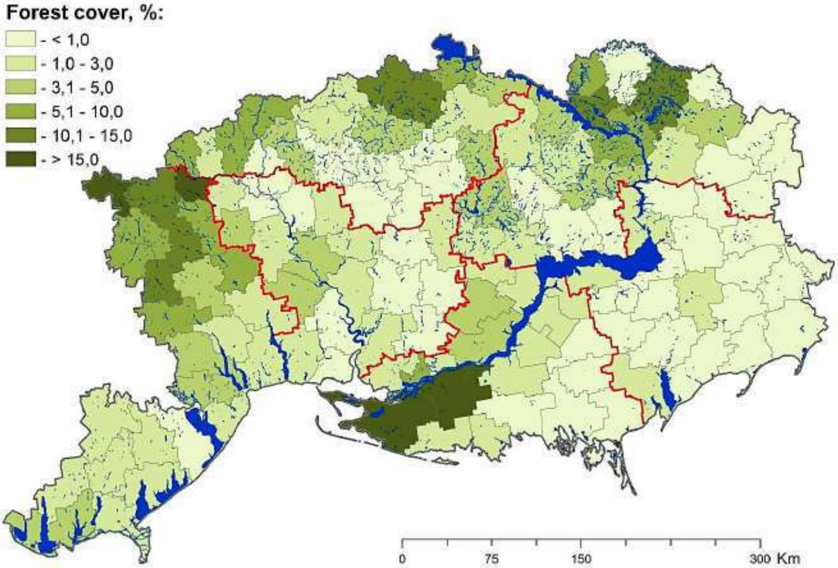

Figure 5. Spatial differentiation of the forest cover of the administrative districts of the Steppe zone

In accordance with the arable land/natural land ratio, the following types of landscape conditions are determined: 70 : 30 – destructive, 60 : 40 – unstable, 50 : 50 – extremely stable, 40 : 60 – minimum stable, 35 : 65 – medium stable, 30 : 70 – stable, 25 : 75 – high stable, 0 : 25 : 100–75 – ecological balance with steady increase of soil fertility. The level of plowed up territories of the studied Steppe region makes up 78.6%, including Dnipropetrovsk region – 80.5%, Zaporizhzhia region – 84.6%, Kirovohrad region – 86.9%, Mykolaiv region – 81.8%, Odesa region – 75.9%, Kherson region – 61.4%.

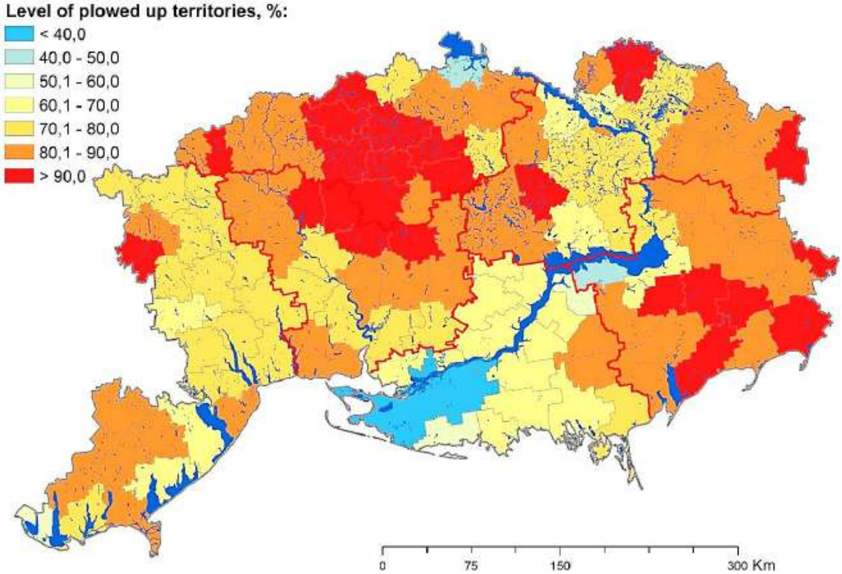

Figure 6. Level of plowed up territories of the studied Steppe zones of Ukraine

Agricultural development of the Steppe zone of Ukraine varies from 20 to 97%, besides, 3 ATU with a total area of 0.80 thousand km^2 (0.5% of the area of the studied region) have high stable and stable landscapes with the level of plowed up territories of 30% and less; 2 ATU with a total area of 4.18 thousand km^2 (2.5%) have the medium and minimum stability of the landscape (level of plowed up territories is 30–40%); 2 ATU with a total area of 2.56 thousand km^2 (1.5%) have the level of plowed up territories within the limits of 40–50% and, respectively, extremely stable landscapes; 123 ATU with a total area of 159.90 thousand km^2 (95.5%) have unstable and destructive level (more than 50% of the plowed up area) of the landscapes. About 18.0% of the studied region territories are plowed up by 90% or more.

One of the most important tasks of protection of forest and forest protective belts is to develop and maintain an optimum percentage of the forest cover differentially for different physical and geographical areas of Ukraine. Protective forest plantings are the basis of optimized ecological systems in agricultural areas, an important component of anti-erosion organization of land management. The productivity of optimized forest agricultural landscapes can be 1.5–2.0 times higher than open treeless areas, which is a reliable reserve for solving food and environmental problems. Forest plantings play an important role in establishing ecological balance, harmonizing the interaction of major ecological systems of the biosphere (Yukhnovsky et al., 2009). The main reason for slowing down the restoration of protective forest plantings is the unresolved legal aspects of their ownership. The planted lands were not subject to stocking, they are accounted for as lands of the reserve, reserve fund and general use by settlement councils. Therefore, it is necessary to regulate the issue of the adequate maintenance of the forest belts by assigning them to the owners of agricultural lands. At the level of the state regulatory acts, it is necessary to anchor the order of priority of the maintenance and service of forest belts, to improve the system of their use, and to take measures to create new field protective plantings at the expense of the local government finances.

The results of studies of economic and environmental development of Ukrainian forestry indicate ecologically unbalanced forest management. There is no well-defined system of measures for forest protection, forest inventory, forest management, forest restoration, protective forest cultivation. There is a need to scientifically justify the organization of environmentally balanced management of forestry activities with a focus on forest restoration through innovative forestry technologies and the development of forest infrastructure. Also, the development and implementation of a system for evaluating the effectiveness of forestry activity management becomes relevant.

CONCLUSIONS

In order to preserve and improve the productivity, restoration, protection and defense of forests, as well as to improve the culture of forestry management, it is necessary to implement measures for forest organization, the main task of which is to determine the boundaries of the territories of forestry enterprises, forest resources, species and age composition of forests; to discover the logging areas, to specify the areas of forest restoration and afforestation; to determine the ways of forests restoration; to specify the division of forests into groups and categories of the degree of protection. The main ways of rational use and restoration of forests are the environmental and economic substantiation of forest improvement measures and the use of wood, the introduction of scientifically sound calculation and distribution of the forest fund, the use of the forest protection system against pests, diseases, forest fires and unauthorized logging, maintenance of an optimum level of forest cover at the required level of restoration of primary forest types in the process of forest exploitation. The results of the conducted study make it possible to substantiate the system of spatial-differential measures of forest restoration and implementation of specific land-and water-protective measures for optimization of the land fund on the basis of adaptive-landscape principles, which is a prerequisite for rational management and rehabilitation of forest and land resources of Ukraine.

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SOIL AND CLIMATIC BONITATION OF AGRICULTURAL LANDS OF THE STEPPE ZONE OF UKRAINE

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INTRODUCTION

Anthropogenic impact on the natural environment has exceeded the potential of its sustainable development, which resulted in a global environmental crisis. In order to overcome it, it is necessary to introduce a differential-territorial environmental management, which, in turn, consists of a comprehensive assessment of the territory of different localization and a plan of actions aimed at restoring the natural balance. Particular attention should be given to the issues of rational and efficient use of agricultural lands, specialization and concentration of agricultural production with due account for the natural or soil and climatic conditions of individual territories, which include climatic conditions, quality of soil and relief. An important role in the organizational works on the rational use of agricultural lands is bonitation of zonal soils, which is a cross-functional assessment of their fertility when comparing agroclimatic conditions, determination of the intensity of agriculture to ensure effective environmentally safe production with optimal use of soil potential. It also characterizes zonal features of soils as a medium for plant life, expressed in quantitative fertility indices – points (from 0 to 100 points) calculated according to soil properties and climatic conditions, the main of which are the content of humus, thickness of the humus horizon, granulometric composition, content of macronutrients, water availability, amount of active temperatures, etc. It is necessary to take into account all causal relationships, in particular the topographic effect, as a general integral function which determines the process of redistribution of heat and moisture in the soil and largely determines the agricultural crops yields. In relation to soil science A. Gerrard called this approach “the integration of geomorphology and soil science” (Gerrard, 1984). Significant spatial differentiation of the relief and natural and climatic conditions largely determines agro-industrial groups of soils and the level of extensive agricultural development of territories in different physical and geographical zones (Lisetskii et al., 2016; Pichura et al., 2017, 2019; Zelenskaya et al., 2018).

Bonitation of soils is a logical continuation of integrated land surveys and the state cadastral valuation of agricultural lands, which in the field of land relations is the basis for establishing land tax, mortgage rates and rent amounts, starting prices for tenders and auctions, and is also used in other fields, related to management of land resources. Cadastral valuation should be directed to maximally accurate account of all conditions that affect the value characteristics of soils (Potravka, 2007; Tanklevska et al., 2015). Therefore, the actual task is to specify points of soils bonitation within the limits of separate land use in conditions of terrain heterogeneity. The current level of development of geoinformation systems, their ability to analyze and solve applied tasks, fully allows this task to be realized.

Academician S. S. Sobolev (1965) noted that bonitation is a specialized classification of soils by their productivity, based on objective characteristics (properties) of the soils themselves, which are the most important for the growth of crops and correlate with the average long-term yield. According to V. V. Dokuchaev (1936) and M. M. Sibirtsev (1951), the basis for soils bonitation should be their natural qualities as the most objective and reliable indicators that can be determined by the measure and importance of the properties laid down in the soil itself. As a matter of fact, the key factor of scientific bonitation of soils is a well-chosen criterion for assessment of soils by points.

V. V. Medvedev (2006) noted that bonitation should be considered as a uniform system "soil-climate-field". Within the terms of the proposed concept, not only the soil is evaluated, but also the components inextricably connected therewith. At least, it includes climate and field, which makes the assessment of soils more objective and extends its application aspects. The researcher also noted that in calculation of bonitation it is necessary to consider the characteristics of relief, since the slope is an important characteristic of the field and could be used directly in the calculations of bonitation without the use of correction coefficients. The author regards the slope exposition as an important factor of fertility and yield, but, unfortunately, the systematic surveys over the soil regimes and crops yield on the slope of different exposition are not enough. Therefore, in V. V. Medvedev's method exposition is not taken into account.

In the California bonitation method, developed by R. I. Storie (1978) and used in the United States for more than 50 years, particular attention is paid specifically to the relief as a control factor for the possibility of using land and determining its productivity. The advantage of this method is that on the basis of the slope of the relief, possible development of slope erosion is considered. Thus, possibility of obtaining excessive results of bonitation is excluded, and the influence of each factor is objectively factored into the overall point of bonitation. In order to determine the soil and climatic potential of the territory of the steppe regions of Ukraine, I. I. Karmanov's (1980) method of zonal soils bonitation was used. The scientist considered bonitation as a quantitative assessment of the fertility of land for the cultivation of certain crops. Assessment criterions are factors, divided into three main groups: natural, economic and scientific-organizational. I. I. Karmanov's method is adapted in practice for the creation of a uniform comparative scales of soil fertility assessment for different physical and geographical conditions.

MATERIAL AND METHODS

In order to create spatial models of soil bonitation in the territory of the steppe regions of Ukraine (Dnipropetrovsk, Zaporizhzhia, Kirovohrad, Mykolaiv, Odesa, Kherson regions) in accordance with a uniform comparative scale of soil fertility assessment, the method of zonal soil bonitation by I. I. Karmanov (1980) was adapted and tested. In the foundation thereof, in addition to the soils properties, the bonitation of the climate with due account for the principal climatic indicators that correlate with yield – the amount of active temperatures, humidity index and climate continentality, is laid. The method reflects the general patterns of spatial distribution of yields by natural physical and geographical zones and allows calculating soils bonitation points for each crop separately (Table 1, see p. 62). Having the data on the relief, it is possible to extrapolate the climatic characteristics of each local element of the landscape, which will make it possible to specify the conditions of the microclimate and, accordingly, establish the soil bonitation point.

Calculation of soil and climatic potential of soils and obtaining of raster models of its distribution should be carried out under the formulas for calculating zonal soils bonitation point in the Raster Calculator of ArcGIS working module.

The magnitude of the coefficient of climate continentality (*CC*) is calculated by the formula:

$$CC = \frac{360(t^{\circ}_{\max} - t^{\circ}_{\min})}{\varphi + 10}, \qquad (1)$$

where $t^{\circ}_{\max}$ – the average monthly temperature of the warmest month; $t^{\circ}_{\min}$ – the average monthly temperature of the coldest month; ϕ – the latitude of the terrain.

Table 1. Calculation bonitation points for different crops by using soil and climatic formulas

Crop	Calculation formula	Note
Cereals	$B = 8.2V \frac{\sum t^{o} \geq 10^{o} \times HF}{CC + 70}$	*HF* more than 0.9 is taken equal to 0.9
Sunflower	$B = 6.8V \frac{\sum t^{o} \geq 10^{o}(HF + 0.2)}{CC + 50}$	*HF* more than 0.7 is taken equal to 0.7
Sugar beet	$B = 4.3V^{'} \frac{(\sum t^{o} \geq 10^{o} + 2000)(HF - 0.2)}{CC}$	*HF* more than 0.9 is taken equal to 0.9; $V^{'} = \frac{4V - 1}{3}$
Perennial grasses	$B = 5.9V^{''} \frac{(\sum t^{o} \geq 10^{o} + 2000)(HF - 0.1)}{CC + 100}$	*HF* more than 1 is taken equal to 1; $V^{''} = \frac{V + 1}{2}$
Annual grasses	$B = 6.8V^{''} \frac{(\sum t^{o} \geq 10^{o} + 1000)HF}{CC + 100}$	
where *B* – bonitation point; *V* – total value of soil properties; $\Sigma t° \geq 10°$ – average annual amount of air temperature above 10 °C; *HF* – humidity factor by Ivanov; *CC* – continentality coefficient.		

Humidity factor (*HF*) is determined by formula:

$$HF = P / E, \tag{2}$$

where *P* – average annual amount of precipitation, mm; *E* – average annual evaporation, g/cm^2.

The total value of soil properties is established in accordance with the coefficients of the total value (*V*) of soil properties from 0.5 to 0.98.

For the detailed local assessment of soils within a separate administrative-territorial units and land users, correction coefficients under environmental and agrochemical indices of soil condition are additionally used. In addition, the ratio and exposure of slope are taken into account. For irrigation conditions, additional irrigation moisture and adverse environmental and soil reclamation properties (groundwater level, salinity type and salinization) should be included in soil bonitation.

Based on the results of spatial geostatistical modeling and the algebra maps of ArcGIS program, cartograms, reflecting points of the soil differences bonitation in the territory of the studied steppe regions of Ukraine, are created. On the basis of the soil bonitation point a group and land-use capability according to the scale of their qualitative assessment (Table 2) was determined.

Table 2. Scale of qualitative soil assessment

Bonitation class	Bonitation point	Group of lands
I	91–100	Soils of high-end quality
II	81–90	
III	71–80	Soils of high quality
IV	61–70	
V	51–60	Soils of average quality
VI	41–50	
VII	31–40	Soils of low quality
VIII	21–30	
IX	11–20	Soils of bottom quality
X	1–10	Unusable soils

The spatial models of the amount of active temperatures, humidity factor and climate continentality were determined based on the extrapolation of the decompositions of the publicly available data *CliWare* (http://cliware.meteo.ru/meteo), additional data of the individual weather stations and the national atlas. In order to determine the value of the total value of soil properties, vectorization of a soil map of Ukraine at scale 1 : 2,500,000 was carried out. The *ArcGIS* zone statistics method calculates the average values of the soil bonitation components for each administrative unit.

RESULTS AND DISCUSSION

The soil cover of the steppe regions of Ukraine is characterized by low-humic soils with a content of humus in a layer of soil of 0–20 cm from 0.30% to 4.75% (Fig. 1, see p. 64). The spatial heterogeneity of the humus content is determined by the complexity of soil cover structure, which is primarily due to zonal factors of soil formation and heterogeneity of hydrothermal conditions, and secondly, to the development of gluten processes in the soil waters due to their waterlogging with melted and rain waters, and thirdly, to an intense manifestation of salination and salinization at shallow groundwater deposits.

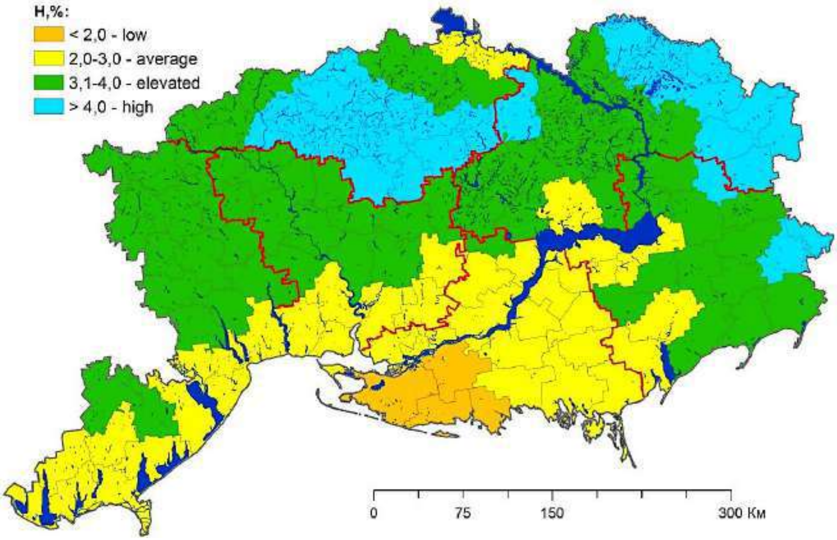


Figure 1. Spatial differentiation of humus (H, %) content in soils of agricultural lands in the Steppe zone of Ukraine

The main types of soils in the regions of the Steppe zone of Ukraine (Fig. 2, see p. 65) are chernozems, which occupy 83.2% of the total agricultural lands area, chestnut and dark chestnut soils – 7.7%. The total area of the studied steppe region was 167.4 thousand km^2, including agricultural lands of 133.5 thousand km^2 (79.7% of the studied area: Dnipropetrovsk region – 15.0%, Zaporizhzhia region – 13.4%, Kirovohrad region – 12.1%, Mykolaiv region – 12.0%, Odesa region – 15.4%, Kherson region – 11.8%), including arables land of 113.5 thousand km^2 (85.0% of the agricultural lands area: Dnipropetrovsk region – 15.9%, Zaporizhzhia region – 14.3%, Kirovohrad region – 13.2%, Mykolaiv region – 12.7%, Odesa region – 15.6%, Kherson region – 13.3%), of which the irrigated lands area is 6.3 thousand km^2 with the proper functioning of the irrigation systems infrastructure ensured (5.6% of the arable land area: Dnipropetrovsk region – 1.8%, Zaporizhzhia region – 0.4%, Kirovohrad region – 0%, Mykolaiv region – 0.3%, Odesa region – 0.4%, Kherson region – 2.7%).

Depending on the type of soils, the spatial differentiation of the value of the total value (V) of the properties of zonal soils, which depends on their agricultural value for the studied steppe region, is from 0.5 for soddy-sand and chestnut- solonetzic soils, which are in the southern part of Kherson region, to 0.98 for typical chernozems, which are more likely to be in Odesa and Kirovohrad regions (Fig. 3, see p. 66).

The humidity factor (HF), calculated by M. M. Ivanov's method is determined by the ratio of the annual amount of precipitation

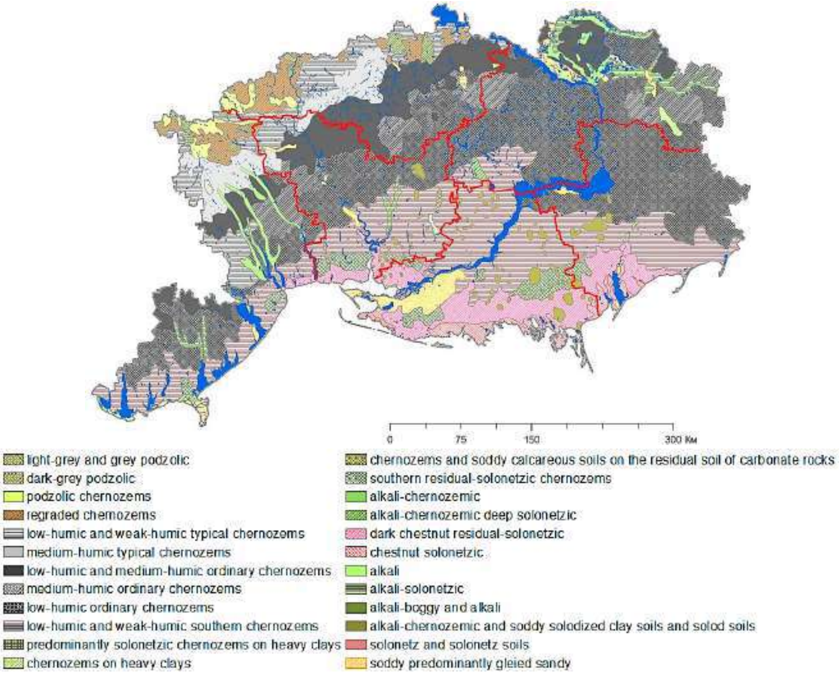


Figure 2. Types of soils in the studied steppe regions

to the annual value of evaporation for the corresponding landscape, it is an indicator of the ratio of heat and moisture, with which the zones of provision of biocenosis with moisture are distinguished. In the territory of the studied steppe region, the value of HF decreases from the northwest to the southeast from 0.72 to 0.30 (Fig. 4). It was established that 33.5% of the territory of agricultural lands is in the territory with very dry (HF 0.33–0.44), dry (HF 0.44–0.55) – 43.3%, semi-dry (HF 0.55–0.77) – 23.2% conditions.

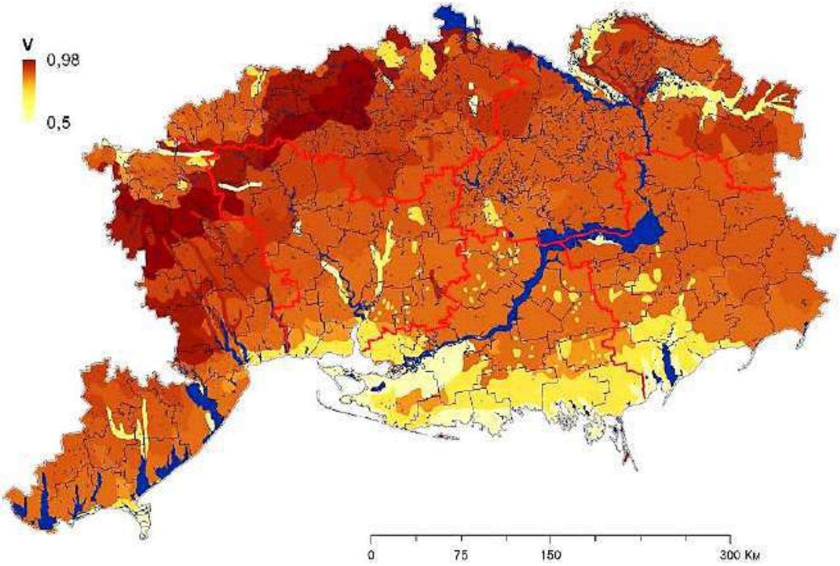


Figure 3. Rasters of spatial differentiation of the total value (V) of the properties of zonal soils in the territory of the Steppe zone of Ukraine

The reverse process is characterized by the climate continentality (CC) index, which at high values characterizes the high amplitude of air temperature, a small amount of precipitation and light winds. In the territory of the studied steppe region, the value of the CC varies within 143.8–167.9 (Fig. 5, see p. 67).

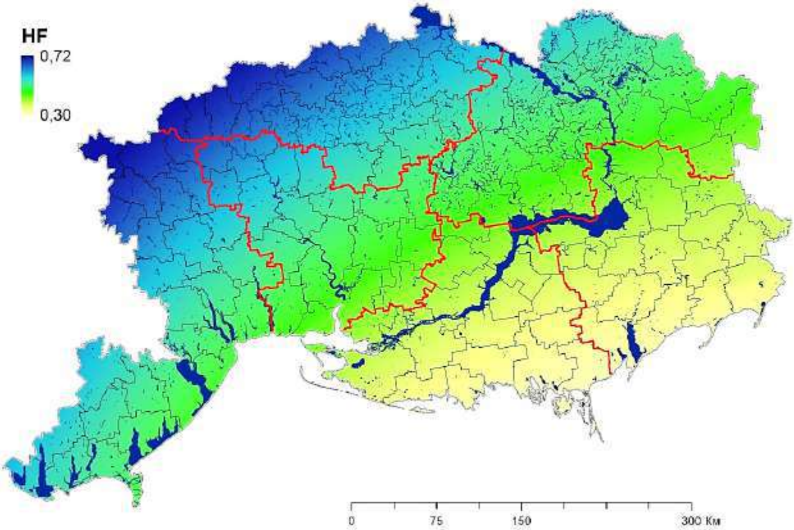


Figure 4. Rasters of spatial differentiation of the values of the humidity factor (HF) in the territory of the Steppe zone of Ukraine

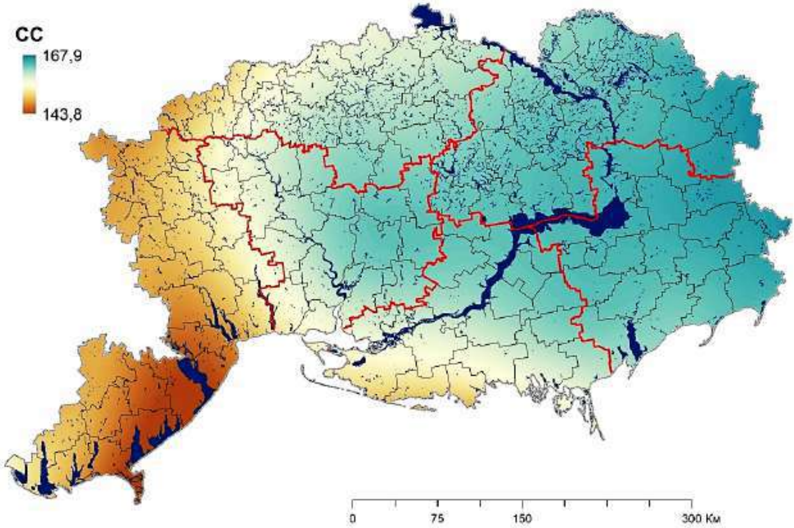


Figure 5. Rasters of spatial differentiation of the values of the climate continentality (CC) index in the territory of the Steppe zone of Ukraine

The bioclimatic potential of agricultural production is considerably related to solar radiation, biochemical accumulation and migration of substances in the soil, which are especially manifested in a frostless season at an air temperature above 10 °C. The average annual amount of active temperatures above 10 °C increases from the northwest to the southeast of the studied territory from 2,793 °C to 3,382 °C (Fig. 6).

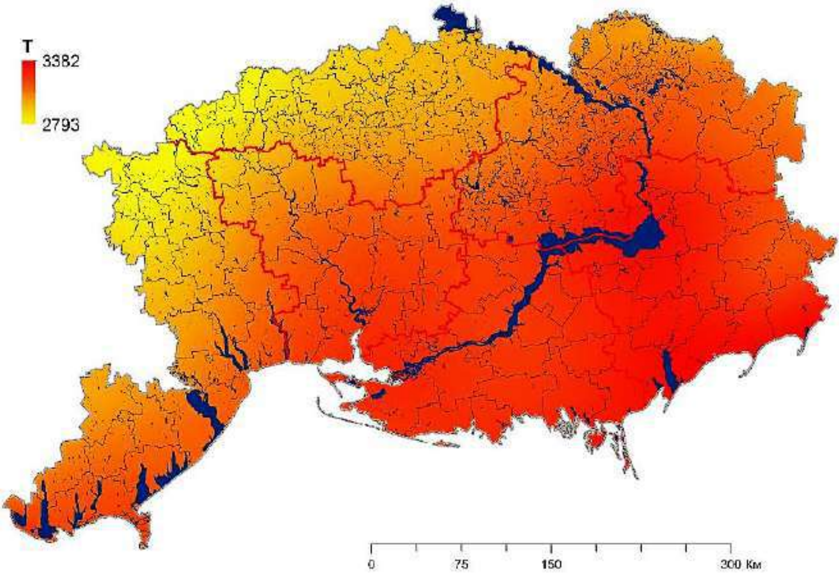


Figure 6. Rasters of spatial differentiation of values of the average annual amount of active temperatures (*T*) above 10 °C in the territory of the Steppe zone of Ukraine

As a result of GIS modeling by using soil and climatic models and the Raster Calculator of ArcGIS 10.1, the calculation of the zonal soils bonitation point for growing grain crops, sunflower, annual and perennial grasses has been calculated within the individual areas of the studied steppe region (Fig. 7, see p. 69) and its individual administrative-territorial units (Fig. 8, see p. 70). The distribution of areas with different values of the soil bonitation point for growing crops under the conditions of the rain crop of agriculture is presented in Table 3 (see p. 71). It is determined that under the existing soil and climatic conditions of the studied steppe region, the most favorable conditions for farming are attributable to the administrative-territorial units of the northwest steppe region, located in Odessa and Kirovohrad regions. The maximum value of a bonitation point for different crops intended for sowing ranges from 67 to 85 points.

In the territory of the Steppe zone of Ukraine, lands of average quality with a bonitation point within the range of 41–60 points, which include ordinary and southern medium- and low-humic chernozems, prevail. There are also some typical chernozems. The area of agricultural land with an average quality of land

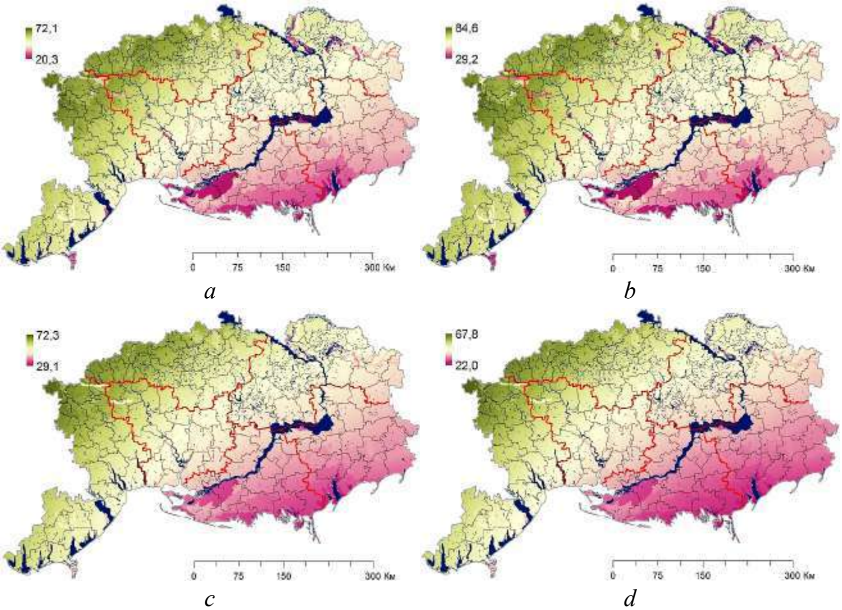
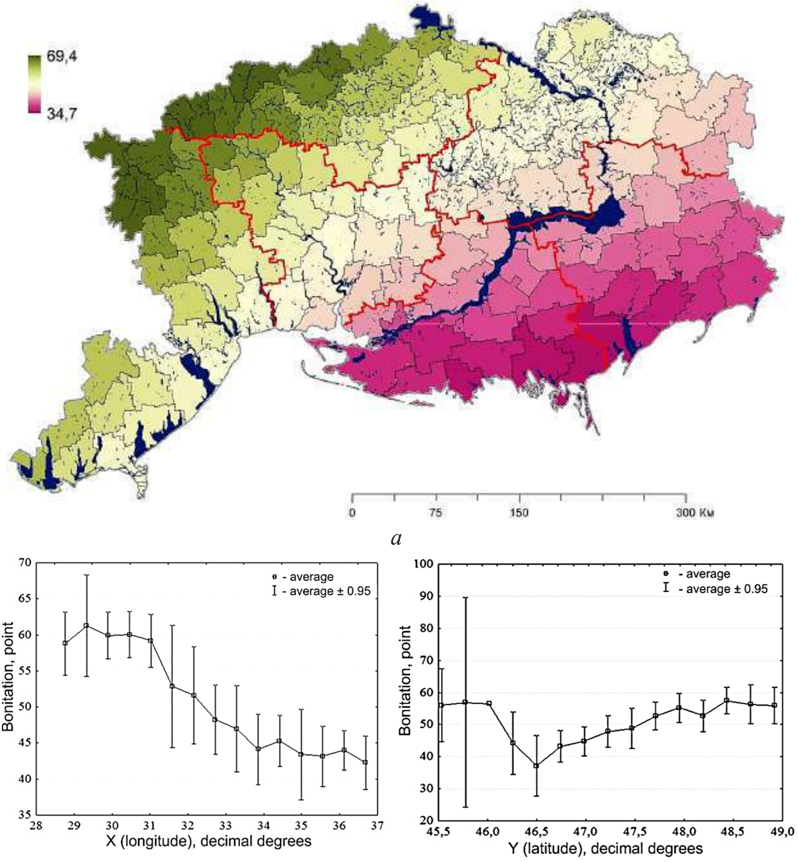


Figure 7. Zonal soils bonitation (points) within the territory of the Steppe zone of Ukraine:

a – growing of grain crops; *b* – growing of sunflower;
c – growing of annual grasses; *d* – growing of perennial grasses



a

b *c*

Spatial distribution function of bonitation (B)point values:

$$B = -47,18X + 0,53X^2 + 26,61Y - 0,26Y^2 + 0,19XY + 66,52 \quad r^2 = 0,78,$$

where X – longitude, decimal degrees; Y – latitude, decimal degrees

d

Figure 8. Spatial distribution of the average value of the zonal soils bonitation (points) within the administrative-territorial units of the Steppe zone of Ukraine:

a – cartogram of spatial distribution of bonitation;
b – heterogeneity of distribution from west to east; *c* – heterogeneity of distribution from south to north; *d* – model of spatial distribution

Table 3. Distribution of agricultural lands according to the soil and climatic potential of growing crops

Group of lands	Bonitation class	Bonitation point	Area, km^2	% to the total area
Growing of cereals				
Low quality	VIII	21–30	1.50	1.12
	VII	31–40	16.33	12.23
Average quality	VI	41–50	47.83	35.83
	V	51–60	47.19	35.35
High quality	IV	61–70	20.48	15.34
	III	71–80	0.16	0.12
High-end quality	II	81–90	—	—
Growing of sunflower				
Low quality	VIII	21–30	—	—
	VII	31–40	1.24	0.93
Average quality	VI	41–50	7.32	5.48
	V	51–60	35.27	26.42
High quality	IV	61–70	49.85	37.34
	III	71–80	38.09	28.53
High-end quality	II	81–90	1.72	1.29
Growing of annual grasses				
Low quality	VIII	21–30	—	—
	VII	31–40	15.61	11.69
Average quality	VI	41–50	48.37	36.23
	V	51–60	48.05	35.99
High quality	IV	61–70	21.05	15.77
	III	71–80	0.43	0.32
High-end quality	II	81–90	—	—
Growing of perennial grasses				
Low quality	VIII	21–30	—	—
	VII	31–40	2.91	2.18
Average quality	VI	41–50	45.36	33.98
	V	51–60	47.07	35.26
High quality	IV	61–70	31.35	23.48
	III	71–80	6.81	5.10
High-end quality	II	81–90	—	—
Total			133.50	100

for growing individual crops varies from 32.0% for sunflower to 72.2% for annual grasses. The territories of agricultural lands with the lowest soil and climatic potential are located in the southern and southeastern parts of the studied steppe region (40 points or less – lands of low quality) in the southern medium-humic, dark chestnut, chestnut solonetzic soils of Kherson and Zaporizhzhia regions. The area of arable lands with low quality land for growing individual crops varies from 1% for sunflower to 13% for cereals. The lands with high and high-end quality (more than 60 points) are located in the northwestern part of the studied area on the regraded, typical and ordinary medium- and low-humic chernozems with the area of agricultural lands from 15.5% for grain crops to 67.2% for sunflower.

CONCLUSION

Approbation of zonal soils bonitation method and the results obtained for the Steppe zone of Ukraine provided a clarification of the spatial differentiation of agricultural lands bonitation, taking into account the soil type and changes in climatic conditions. Raster models were created and spatial patterns of distribution of the four components of the zonal soils bonitation were established: the total value of soil properties, humidity index, coefficient of climate continentality, average annual amount of active temperatures greater than 10 °C. It was determined that in the territory of the studied steppe region, the agricultural lands of average quality prevail. Depending on the type of crops growing, their area varies from 32.0% to 72.2%, with low quality – from 1% to 13%, with high and high-end quality – from 15.5% to 67.2%. Bonitation points are established on the basis of a unified scale of assessment of land quality, which allows to objectively calculate the bioproductive potential of the territory, to determine the area of agricultural lands in terms of their qualitative characteristics, to clarify the normative monetary assessment and to determine the optimal level of agricultural land tax, to adjust irrigation rates in order to reduce the volume of water intake from natural water sources, to justify measures and terms for the reclamation of degraded lands.

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LONG-TERM CHANGES IN THE STABILITY OF AGRICULTURAL LANDSCAPES IN THE AREAS OF IRRIGATED AGRICULTURE OF THE UKRAINE STEPPE ZONE

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INTRODUCTION

In the context of global climate change and effective economic activity of land users in the Steppe zone of Ukraine, the use of irrigation reclamation is an urgent issue to obtain high yields of agricultural crops (Lisetskii et al., 2016; Beznitska, 2017; Pichura et al., 2019). With their beginning, there were changes in the conditions for the functioning of all natural environment components, in particular, the direction and speed of soil processes changed (Volobuev, 1974; Rasmussen et al., 2007; Lisetskii et al., 2016; Dudiak et al., 2019). The results of these changes can have both a positive effect (improvement of moisture supply, increase in productivity, etc.) and a negative one (the processes of flooding, salinization, alkalization, waterlogging, leaching of nutrients into the lower soil profile, which is difficult for plants to reach, and an increase in the amount of nutrient removal with the harvest) (Petrichenko et al., 2013; Martsinevskaya et al., 2018). The direction and intensity of the manifestation of negative phenomena on agricultural and adjacent lands depends primarily on the climatic and hydrological conditions of the region, the volume of irrigation water supply (Pichura et al., 2018).

Extensive use of land resources has led to an imbalance in the natural state of soil fertility, significant deterioration of their fertility, disruption of the ecological balance of the environment, reducing the efficiency and speed of natural soil-forming processes, increasing energy costs for stable crop yields (Dudiak et al., 2019;

Mayovets et al., 2021; Vdovenko et al., 2022). The area of lands with a high degree of degradation in Ukraine is more than 1.1 million hectares, most of them in the steppe zone. In particular, the low culture of agriculture leads to a violation of technology and timing of tillage, protection of plants from weeds, pests and diseases, which negatively affects the reproduction of soil fertility (Dudiak et al., 2020, 2021). This exacerbates the problems of humus, agrophysical and reclamation conditions and leads to a decrease in soil fertility and environmental safety of land use (Terhoeven-Urselmans et al., 2010; Fagnano et al., 2012; Pichura et al., 2021). Intensification of agricultural production, application of chemicals, reclamation and mechanization leads to a decrease in the content of humus in the fertile soil layer and the deterioration of its ecological, agrochemical and physical properties (Luo et al., 2018; Li et al., 2020; Pichura et al., 2021). Therefore, it is important to determine the spatial and temporal patterns of differentiation of soil degradation processes in order to develop adaptive environmental measures for environmentally friendly land use based on adaptive landscape, basin and geosystem principles (Lisetskii et al., 2014; Pichura et al., 2017).

Considering the current state of irrigated agriculture in the Steppe zone of Ukraine, the unsatisfactory technical level of a significant part of irrigation systems, as well as the level of resource and technological support for both irrigation and growing crops on irrigated lands, it can be argued that there is a high potential danger of developing negative processes and phenomena (Pichura et al., 2015; Ukrainskiy et al., 2020). Therefore, works related to the study of the irrigated lands state are of particular importance both in terms of the timely determination of negative processes and phenomena, and in order to determine the actual ecological and agro-ameliorative state and sustainability of agricultural landscapes. They should become the basis for the development and implementation of a set of measures to improve the condition and increase the productivity of irrigated and adjacent lands.

Long-term assessment and forecasting of groundwater levels, as well as determining the resistance to flooding of agricultural landscapes in areas of long-term irrigated agriculture is the main indicator of the influence of climatic and anthropogenic conditions in the irrigation zone of the Steppe of Ukraine (Medvedev et al., 2006; Breus et al., 2019, 2020). The analysis of flooding and its occurrence is the main component of the reclamation regime, which affects the formation of fertility indicators of irrigated lands and, accordingly, the crop yield (Domaratskiy et al., 2018, 2020).

The purpose of the research is to determine long-term changes in the stability of agricultural landscapes in the areas of irrigated agriculture in the Steppe zone of Ukraine (on the example of the south of the Kherson region).

MATERIAL AND METHODS

Spatial and temporal assessment of the stability of agricultural landscapes over a long period (130 years) was carried out on the basis of archival spatial data for the territory of the Dnieper district of the Taurida province (Fig. 1, see p. 77), which included the location of observation wells (135 stations), groundwater level marks. In addition, modern data from the State Agency for Water Resources of Ukraine, the Kakhovka hydrogeological and reclamation expedition, and radar topographic surveys for a digital elevation model construction (DEM) were used.

Spatio-temporal research, modeling and forecasting of the stability of agricultural landscapes, determination of long-term regularities in the formation of the main parameters of climatic conditions (air temperature, amount of precipitation) and anthropogenic load on the territory of the Dnieper province were carried out using the methods of multivariate statistics and geostatistical analysis. Time series and forecasting (TSF) work modules of the STATISTICA 10.0 software product were used for temporal analysis. For spatial modeling, the method of the radial basis function of the Geostatistical Analyst module of the ArcGis 10.1 program was used.

Based on many years of original research on assessing the stability of agrolandscapes (Pichura et al., 2014), depending on the levels of groundwater occurrence (GWL), the following

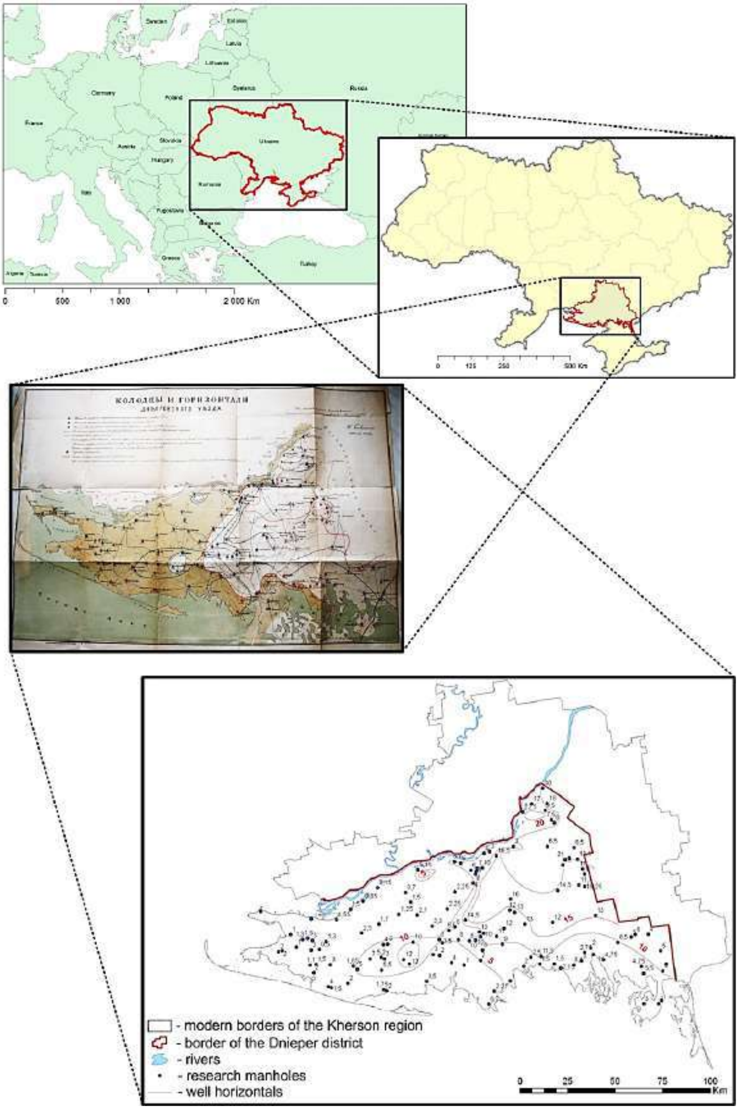


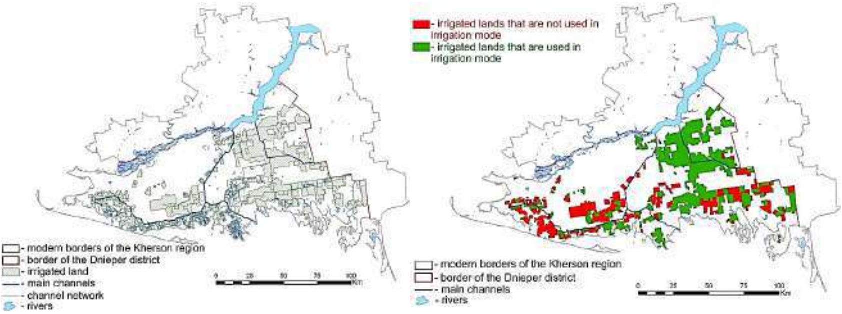
Figure 1. Spatial arrangement of research manholes with marks of groundwater levels in the territory of the Dnieper district of the Tauride province. Initial data – archival materials of N. Golovkinsky (1892)

classification of qualitative conditions was proposed: *low stability* of agrolandscapes – these are areas that are characterized by constant flooding at the beginning and end of the growing season or have a high risk flooding (GWL < 2.0 m), and are also subject to the active manifestation of the processes of salinization and solonetzization of soils; *medium stability* – these are territories that are partially subject to flooding and with significant amounts of precipitation (for the dry steppe zone more than 400 mm per year and more than 250 mm during the growing season with intensive irrigation) have a risk of raising the GWL to 2.0 m (GWL – 2.1–5.0 m), which also leads to the formation of soil degradation processes; *high stability* – these are territories that are not subject to flooding by groundwater and, accordingly, the processes of salinization and alkalinity of soils (GWL > 5.0 m).

RESULTS AND DISCUSSION

For the base period of our research (1892), the Dnieper district was part of the Taurida province, its total area was 11,470.5 square versts, i.e. 1,305.5 thousand hectares. As of 1892, the total plowing of the county was 24.0–26.0% (313.0–340.0 thousand hectares), the main cultivated crops were spring wheat, rye, barley, corn, and soybeans. Nowadays, this territory (the south of the Kherson region of Ukraine) is plowed by 60.0% (723.0 thousand hectares), the main cultivated crops are winter wheat, barley, sunflower.

In the entire Kherson region, the area of irrigated land is about 426.4 thousand hectares, which is one fifth of all agricultural land in the region, including: Kakhovka irrigation system (243.1 thousand hectares), North Crimean Chanal and Krasnoznamensk irrigation system (102.0 thousand ha), Ingulets irrigation system (18.2 thousand ha), local irrigation systems – 21.2 thousand ha, local irrigation – 40.7 thousand ha, areas of irrigated land use for 2003–2020 amounted to 250.0–315.0 thousand hectares. The constructed irrigation systems, the main part of which is located within the boundaries of the former Dnieper district, is 70.0% of the entire irrigated territory of the Kherson region (Fig. 2, see p. 79) and they are the largest type of anthropogenic load on the agricultural landscape, an indicator of which can be the density of their distribution, spatial differentiation of levels groundwater and land resistance to flooding.



a *b*

Figure 2. Modern transformation of agricultural landscapes in the south of the Kherson region by irrigation reclamation (within the boundaries of the former Dnieper district):
a – distribution of the hydraulic network;
b – distribution of irrigated lands and their use

Irrigation load for the entire territory of the Kherson region was determined by spatial modeling of irrigation canals density using the Line Density of Spatial Analyst tool, which made it possible to identify spatial patterns in the distribution of hydraulic load (an indicator of the density distribution of the hydraulic network) on irrigated lands in the range of 0–100% (Fig. 3, Table 1 (see p. 80)).

High and very high hydraulic load was noted on an area of 5.8 thousand hectares (1.36% of the area of irrigation of the Kherson region), the area with an average level of load is 118.6 thousand hectares (27.84%), most of which are located in borders of the former Dnieper district. A low level of load is recorded on an area of 121.54 thousand ha (28.53%), 180.06 thousand ha (42.27% of the area of irrigation of the Kherson region) is characterized by a very low load.

The load on the distribution density of the hydrotechnical network in the agricultural landscapes of the Kherson region increases significantly from north to south and from east to west, which determines the distribution of the area of irrigated lands with different levels of groundwater.

There are large areas of free-flowing sands, the so-called Oleshky sands, in the western half of the study area. They start

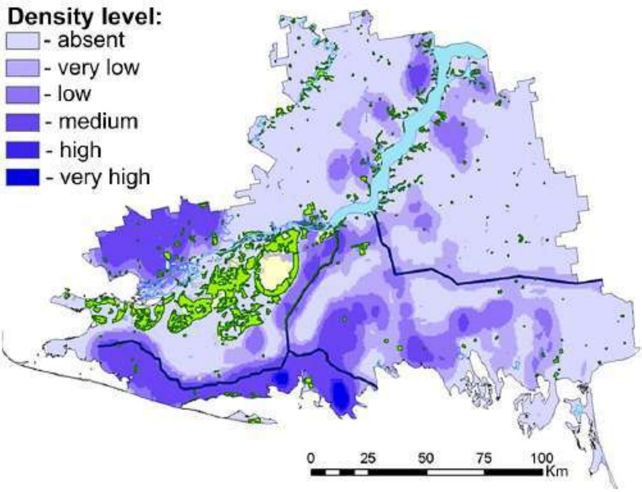
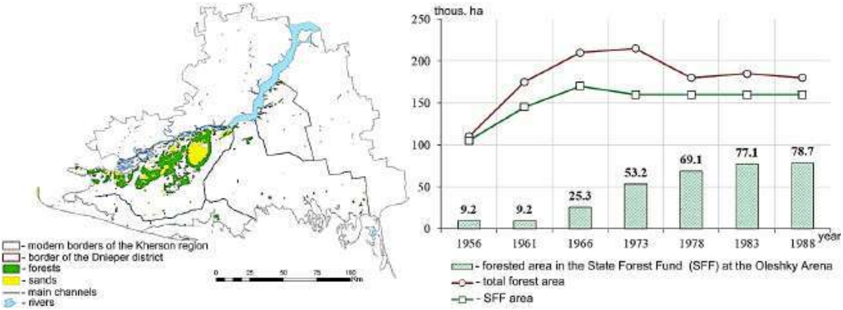


Figure 3. The level of hydraulic load (an indicator of the density distribution of the hydraulic network) on irrigated lands in the Kherson region

Table 1. The hydraulic network placement density on Kherson region agricultural lands

Density of hydraulic network placement, %		**Agricultural lands**			
		Total		**Including irrigated land**	
		thousand ha	**%**	**thousand ha**	**%**
absent	<5.0	1,544.99	78.35	—	—
very low	5.1–10.0	180.06	9.18	180.06	42.27
low	10.1–20.0	121.54	6.17	121.54	28.53
medium	20.1–60.0	118.61	6.02	118.60	27.84
high	60.1–70.0	2.48	0.13	2.48	0.58
very high	70.1–100.0	3.31	0.17	3.31	0.78
Total		1,971.0	100.0	426.0	100.0

from the city of Kakhovka and stretch intermittently down the Dnieper and the estuary to the Kinburn Spit. The area of sands amounted to 161.2 thousand hectares, and taking into account the gaps not covered with sand, – 210.0 thousand hectares. The "Journal of General Useful Information" for 1,837 indicates that the area of forests on the sands of the lower Dnieper, which in 1,802 amounted to more than 5,000 hectares, by 1,832 fell to almost zero. Experimental work on fixing flying sands began at the end of the 18th century, but they acquired a systematic large-scale character in 1830–1840 in connection with the intensification of works on artificial afforestation. However, during the period of general surveying and allotment of land to peasants, which lasted about 30 years (1859–1890), turned into a disaster for forests, including plantations on the sands of the Lower Dnieper. According to Bulatovich (1887), many wooded areas of sands were converted "to their original state" (Popov et al., 1997). The history of afforestation on the Oleshky sands was divided into two stages: protective and reclamation and forestry. At the first century-old stage, the main goal of the work was to fix the sands and create conditions for intensive agriculture: horticulture, viticulture, tobacco cultivation, etc. The second stage of the Lower Dnieper sands development began in the late 1940s. The dynamics of the Kherson region forests in the period from 1956 to 1988 can be traced according to the materials of periodic forest fund surveys. In 1956, the area of the State Forest Fund (SFF) of the region was estimated at 111 thousand hectares, of which less than 10.0% (9.2 thousand hectares) was covered with forest. From 1956 to 1966, about 70.0 thousand hectares of sandy lands were transferred to the SFF, after which its total area remained practically unchanged. At the cost of huge efforts and expenses, over 32 years (1956–1988) the forested area was increased by 8.6 times – from 9.2 to 78.7 thousand ha (Fig. 4, see p. 82). This contributed to the large-scale consolidation of the sands distribution and intensively transpiring forest vegetation, depleting soil moisture, contributed to a decrease in the level of groundwater and a reduction in flooding areas. However, on the Lower Dnieper sands there are numerous shallow depressions, the afforestation of which is still an unresolved problem. Currently, the prospects for forest reclamation of sands are assessed not only in environmental and economic terms, but also in ecological terms.



a *b*

Figure 4. Location of Oleshky sands (*a*) and dynamics (*b*) of their afforestation

One of the most significant manifestations of the anthropogenic impact on the regional geosystem of the Kherson region is the transformation of the ecosystem of the Dnieper River (Pichura et al., 2017, 2018), associated with the disruption of relationships between abiotic and biotic components. As a result of large-scale hydrotechnical construction, the river regime of the river was artificially transformed into a lake regime, which led to a sharp slowdown in water circulation and the appearance of extensive zones of stagnation. Although the creation of the reservoirs of the Dnieper cascade and the Kakhovka hydroelectric power station made it possible to significantly increase the water resource and energy potential of Ukraine, it had a negative impact on the environment, especially the lower reaches of the Dnieper, causing a decrease in the river flow, a rise in the level of groundwater, especially in the coastal part, and an increase in the volume of underground runoff, and an increase in the level of groundwater pollution, increased abrasion of the coastal zone.

To determine the general patterns of temporal formation of climatic conditions for the period of the 19th–21st centuries, the actual values of meteorological data were converted using the “4253H filter” (Fig. 5). This filtering method makes it possible to obtain a smoothed series, while maintaining the main characteristics of the original series. As a result of the analysis, significant differences in climatic conditions were determined for two qualitatively different periods of farming. Throughout the entire time period of change in the average annual air temperature, a positive trend component is observed, the extremum of which coincides with the beginning of the 21st century, and long-term cycles of different dimensions are also observed in the formation of humidification conditions with a positive trend component of the process, starting from the middle of the 20th century.

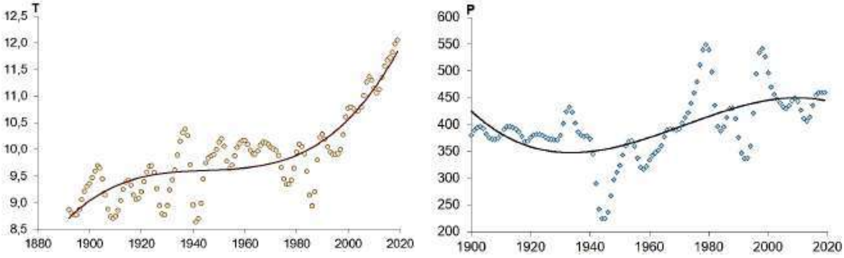


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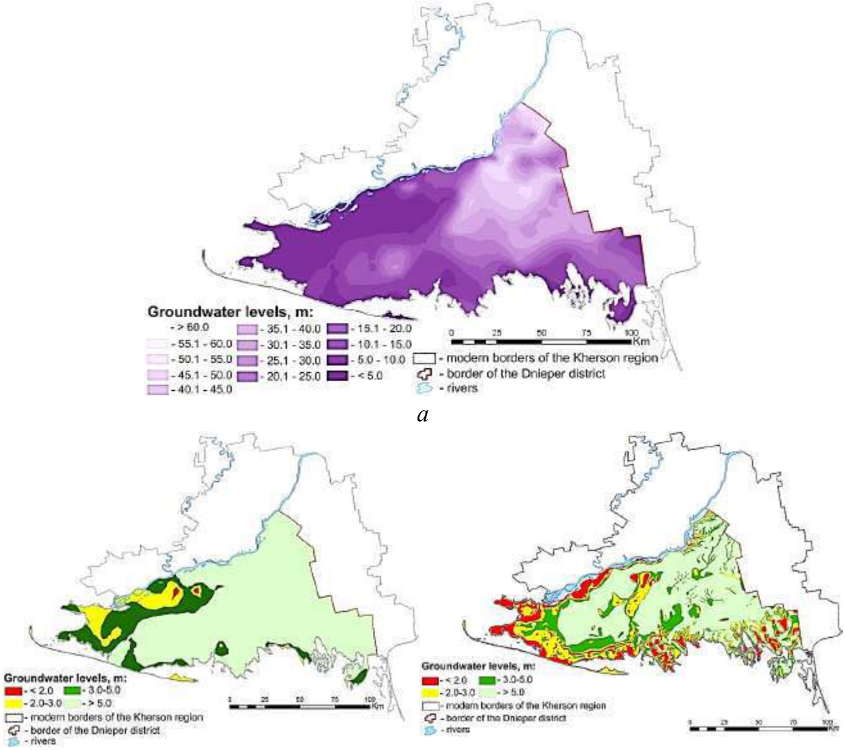
Figure 5. Dynamics of changes in climatic indicators over the period of research (1892–2020):

a – average annual air temperature, °C;
b – the amount of annual precipitation, mm

Compared with the end of the 19th century, by now the average annual temperature has increased by 3.0 °C (from 9.0 °C to 12.0 °C), the amount of annual precipitation has increased by 70.0 mm (from 390 to 460 mm). The steppe zone of Ukraine is referred to the territories of risky agriculture due to extreme climatic conditions, manifestations of drought and wind erosion. Cyclical components of long-term formation of climatic indicators were: air temperature – 8 years, precipitation – 11 years. In particular, the precipitation changes cyclicity in the steppe zone is in the asynchronous pattern of changes relative to temperature. As a result of seasonal analysis, the manifestations of warming during the first 10 months were determined by an average of 2.6 °C, in the period May-October relative to long-term values there is an increase in precipitation by 90.0 mm, which increased the frequency of unproductive moisture and water erosion during the growing season. In addition, the main climatic indicator, which significantly affects the rise in the level of groundwater and, accordingly, the change in the hydrological regime of agrolandscapes in the zone of irrigated agriculture, is the manifestation of stormy precipitation.

Using the results of N. Golovkinsky's archive data, a map of the groundwater level in the territory of the Dnieper district as of 1892 was constructed using geostatistical modeling methods. The spatial distribution of the groundwater level varies from 0.5 m (the coastal part and the Oleshky Sands zone) to 65.0 m central and northeastern part of the study area) (Fig. 6, *a*, see p. 85). Based on the constructed maps, the dynamics of the groundwater level, considering the hydrogeological conditions and the DEM of the study area at the end of the 19th and beginning of the 21st centuries. the areas characterized by certain GWL values are determined: 1892 (Fig. 6, *b*, see p. 85): <2.0 m – 4.1 thousand ha (0.3% of the total area), 2.0–3.0 m – 97.9 thousand ha (7.5%), 3.0–5.0 m – 212.4 thousand ha (16.3%), >5.0 m – 991.0 thousand ha (75.9%); 2020 (Fig. 6, *c*, see p. 85): <2.0 m – 179.1 thousand ha (13.7%), 2.0–3.0 m – 174.3 thousand ha (13.4%), 3.0–5.0 m – 244.7 thousand ha (18.7%), >5.0 m – 707.3 thousand ha (54.2%). Over a long period of research under the conditions of climatic and anthropogenic changes, there has been a significant increase in GWL to critical levels in the coastal and near-chanal zones of irrigated areas. At the beginning of the XXI century, due to a 1.4-fold decrease in the area with a groundwater level >5.0 m, an increase in the area with a groundwater level <2.0 m by 44 times, with a groundwater level of 2.0–3.0 m – by 1.8, and with a groundwater level of 3.0–5.0 m – by 1.15 times. A comparative assessment of the territory of the south of the Kherson region over a long period showed a steady pattern of reducing the sustainability of agricultural landscapes (Fig. 7, see p. 86), which is reflected in an increase in areas with a low level of sustainability by 175 thousand hectares, an average level – by 108.7 thousand hectares and, accordingly, in reducing the area with a high level of stability by 287.3 thousand hectares. Variation in the dynamics of stability of agricultural landscapes over the last 13 years of the 21st century (Fig. 8, see p. 86) was insignificant



a

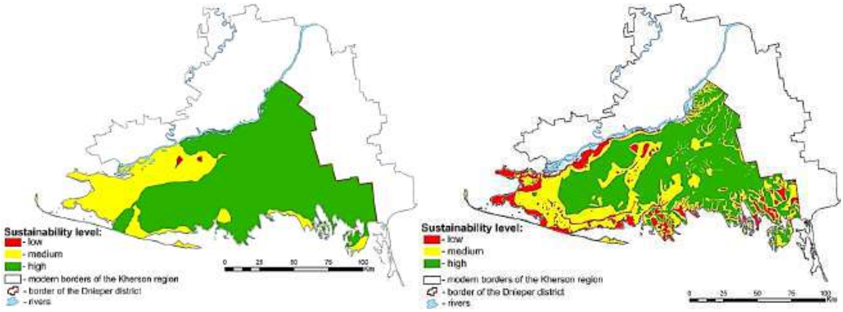
b *c*

Figure 6. Distribution of groundwater levels (GWL) in the south territory of the Kherson region by irrigation melioration (within the boundaries of the former Dnieper district):

a – spatial differentiation of GWL as of 1892;
b – differentiation of the territory beyond the GWL as of 1892;
c – differentiation of the territory beyond the GWL as of 2020

and amounted to: low level of resistance – 147.0–258.9 thousand ha (V = 19.0%), medium – 395.3–434.0 thousand ha (V = 3.0%), high – 651.2–756.1 thousand ha (V = 4.0%).

With the use of zonal statistics, the spatial pattern of the hydrotechnical network density and the dynamics of groundwater levels was determined. This provided an opportunity to clarify the buffer zone and the degree of influence of the hydrotechnical network on the agricultural landscape of the Kherson region (Fig. 9, see p. 87): no or very low load was



a *b*

Figure 7. Spatial stability differentiation of agrolandscapes by the level of groundwater occurrence on the territory of the Kherson region within the boundaries of the former Dnieper district, Taurida province: *a* – as of 1892; *b* – as of 2020

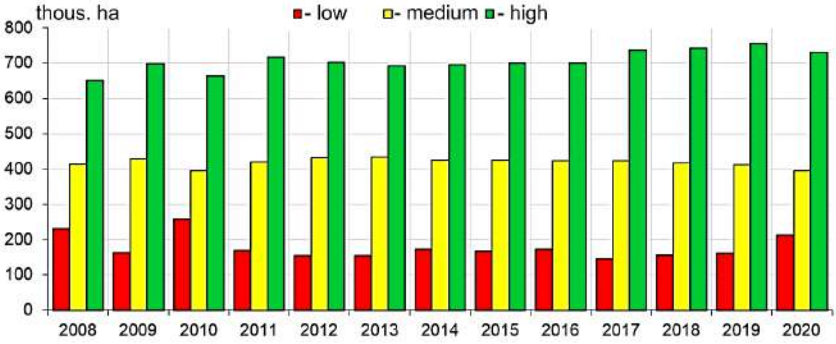


Figure 8. Dynamics of agricultural landscapes sustainability in the Kherson region

determined on 73.9% (1457.1 thousand ha) of the territory, low – 6.1% (119.7 thousand ha), medium – 1.9% (234.9 thousand ha), high – 6.8% (134.1 thousand ha), very high – 1.3% (25.3 thousand ha). The largest specific hydrotechnical load, taking into account the occurrence of groundwater levels, was determined within the boundaries of the former Dnieper district, it amounted to 42.3% of its total area of agricultural landscapes: low – 7.5%, medium – 20.3%, high – 11.4%, very high – 3.1%.

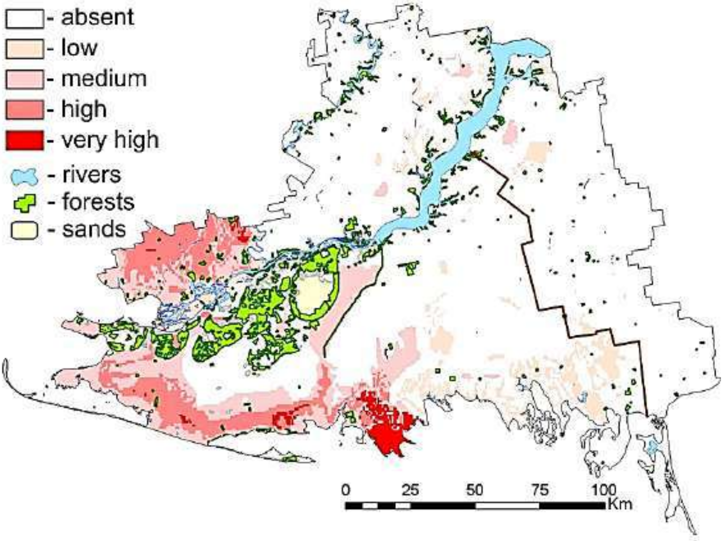


Figure 9. Spatial regularity of the hydrotechnical load influence, taking into account the occurrence of groundwater levels on the agricultural landscape of the Kherson region

As a result of modeling, a direct spatial dependence of the hydraulic network density (anthropogenic load) on the agricultural landscapes stability in the Steppe zone of Ukraine irrigation reclamation was determined, considering the occurrence of groundwater levels.

CONCLUSION

As a result of a comparative analysis of the hydrogeological situation for two periods (1892 and 2020), it was found that the stability of agricultural landscapes in the zone of irrigation reclamation of the Steppe of Ukraine is determined by different conditions of climatic and anthropogenic factors influence. Taking into account the historical patterns of the agriculture development in the territory of the Dnieper district and the results of spatial modeling, territories with low (4.1 thousand hectares – 0.3% of the total area) and medium (310.3 thousand hectares – 23.8%) the level of agricultural landscapes sustainability, which are located in the lower reaches of the Dnieper. Low level of agrolandscapes sustainability in the 19th century was caused by massive deforestation in this area. To the date, the spatial and temporal conditions for the formation of agricultural landscapes sustainability have changed dramatically over 130 years. The anthropogenic load on agrolandscapes has increased significantly, which has led to an increase in the sensitivity of agrolandscapes to climate change. An 8.6-fold increase in the area of forest plantations in the area of the Oleshky sands was accompanied by an increase in the stability of the adjacent agricultural landscapes, however, large-scale hydrotechnical construction led to a deterioration in the stability of landscapes in the lower reaches of the Dnieper. Large-scale agricultural development of the territory and the development of irrigated agriculture has led to the activation of land degradation processes, soil fertility and the deterioration of the stability of agricultural landscapes over large areas. As a result of spatial modeling, to the date, significant areas of agricultural land and adjacent territories have been recorded in the irrigation zone with low (179.1 thousand ha – 13.7% of the total area) and medium (419.0 thousand ha – 32.1%) level of sustainability. The spatial regularity of the distribution density of the hydraulic network and the dynamics of groundwater levels was determined, which made it possible to clarify the buffer zone and the degree of the hydraulic load influence on the agricultural landscape of the Kherson region. It was determined that within the boundaries of the former Dnieper district, the hydraulic load is 42.3%, incl. low – 7.5%, medium – 20.3%, high – 11.4%, very high – 3.1%. A comparative analysis of the situations of two periods showed that large-scale agricultural land development and an unbalanced land use culture lead to constant and almost irreversible processes of reducing the stability of agricultural landscapes in areas of irrigation reclamation.

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SPATIAL DIFFERENTIATION OF REGULATORY MONETARY VALUATION OF AGRICULTURAL LAND IN CONDITIONS OF WIDESPREAD IRRIGATION OF STEPPE SOILS

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INTRODUCTION

At the end of the XX century, anthropogenic impact on the environment has exceeded its capacity for sustainable development, which has led to the global environmental crisis of landscape and aquatic ecosystems (Pichura et al., 2017). The settlement of this situation requires the introduction of territorial management related to comprehensive evaluation of multi-level territorial structural units to develop an action plan for restoration of the natural balance in accordance with local conditions of specific physiographic zones.

Spatial and temporal differentiation of agro-climatic conditions and of farming standards cause qualitative condition of agricultural landscapes, change of ecological, ameliorative and agrochemical properties of soil fertility, which are components of quality class of zonal soils and regulatory and monetary valuation of agricultural land (Beznitska, 2017; Dudiak et al., 2019, 2020). Stocks of nutrients and their availability to plants, as well as reserves of productive moisture (sum of precipitation and irrigation) are closely dependent on the natural and climatic conditions of agro-landscapes (features of releif, soil-forming rocks, climate, hydrogeological conditions, etc.) and system of agriculture, which ultimately determine the volume and quality of crops (Medvedev et al., 2006; Domaratsky et al., 2018). Ecological, ameliorative and agrochemical properties of agricultural landscapes are characterized by high spatial heterogeneity of distribution within the same soil differences of 50 to 70%, resulting from the process of soil formation and farming standards (Medvedev et al., 2009; Zelenskaya et al., 2018).

An assessment of the rate of pedogenesis under natural conditions (Lisetskii, 2012; Jensena et al., 2020) showed that the soil is forming slowly and can be considered an almost irreparable resource under the economic planning horizon. This determines the great importance of assessing the quality of soils both in a utilitarian (resource) aspect and in terms of environmental functions performed by the pedosphere.

Climate is the most important abiotic factor of the geographical environment, which is functionally linked to most of its components and determines the processes of soil formation of zonal soils (Pichura et al., 2019; Liab et al., 2020). In particular, the spatial differentiation of climate impacts is caused by morphometric characteristics of the relief of agro-landscapes, the ratio of components of natural (biocenoses, water resources, wetland ecosystems, etc.) and developed (arable land, settlements, roads, etc.) landscapes (Storie, 1978; Buryak et al., 2014).

Soil quality class determination is the basis of the regulatory and monetary valuation of agricultural land, a characteristic of spatial differentiation of quality and fertility of soils for production. The value of the quality class determination quantitatively expresses the properties of the soil and its suitability for the growth and development of agricultural plants. The results of the conducted soil quality class determination are used for rational planning of economic activities, which allows to take into account the natural and climatic potential of soils and the degree of anthropogenic degradation of the soil cover. This is obligatory to establish all cause and effect relationships of agro-landscape ecosystems, including the impact of relief, as a general integral function, which largely determines the spatial differentiation of soil cover and soil formation processes (Rasmussen et al., 2007; Lisetskii et al., 2014, 2017).

Soil quality class determination is a logical continuation of comprehensive land surveys, the basis for monetary valuation of agricultural land. The main objective of soil quality class determination is to determine the relative quality of soil based on its fertility and to compare the soils by their natural and acquired properties (Dudiak et al., 2019).

In this context, there is a need to objectively valuate the agricultural land, which is necessary for creating spatially coordinated thematic maps of soils and climatic quality class of soils. Soils quality class maps are a spatially discrete model needed to develop adaptive soil protection measures at different territorial levels of agricultural production management and to ensure sustainable land use.

The purpose of the research is to determine ecological, agro-ameliorative and climatic patterns of spatial differentiation of regulatory and monetary valuation of agricultural land in the steppe soil irrigation zone applying advanced methodology of zonal soils quality class determination and GIS technologies.

DATA AND METHODS

Soil quality class determination in the steppe soils irrigation zone has been carried out based on the example of Kherson region of Ukraine (Fig. 1, see p. 95) applying the comparative study of I. I. Karmanov’s soil and climatic quality class determination model (1980, 2012, 2013) and author’s advanced ecological, agro-ameliorative and climatic model.

The territory of Kherson region is located within seven natural agricultural areas. The area of agricultural lands of Beryslavsky natural-agricultural district is 415.2 thousand hectares. The soil cover of the district consists mainly of southern black soil, which is characterized by a humus profile with a thickness of 53–54 cm, the humus content is 3.4–4.2%. Nyzhnosirogozhsky natural-agricultural area includes about 490.3 thousand hectares of agricultural land. More than 80% of the area is occupied by highly productive southern saline black soils, which are under the influence of deflation, so the humus content is in the range of 2.7–3.4%.

Within the Belozersky natural-agricultural district the area of agricultural lands includes 104.8 thousand hectares. The soil cover of the district is represented by dark-chestnut soils in a complex with saline soils, which occupy about 70% of arable land. Soils are characterized by a developed humus profile with a thickness of 52–58 cm, a small amount of humus (1.9–2.7%), and are constantly exposed to deflation. The area of agricultural lands of Oleshkovsky natural-agricultural district is 47.3 thousand hectares. Dominated by saline black soils mainly of sandy mechanical composition, characterized by low humus content (about 0.96%), strong soil profile, low absorption capacity, poor structure, high permeability, low moisture

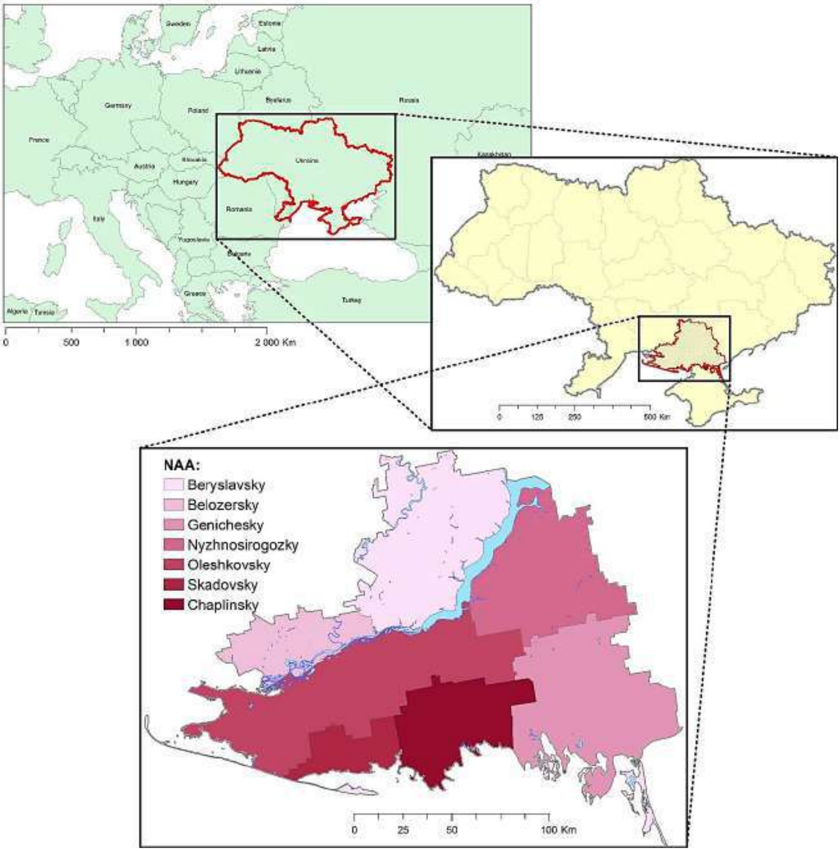


Figure 1. Spatial location of Kherson region and its division into natural agricultural areas (*NAA*)

content and low nutrient supply. Skadovsky natural-agricultural district includes 272.2 thousand hectares of agricultural land. The soil cover is represented mainly by dark-chestnut soils and their complexes with saline soils. Soils are characterized by light mechanical composition, low and medium humus content (0.83–1.7%), well-developed humus profile with weak structure, characterized by significant water permeability on slightly saline soils. Within the Chaplynky natural-agricultural district the area of agricultural lands is 236.7 thousand hectares. The area of agricultural lands of Genichesky natural-agricultural district is 349.5 thousand hectares. The soil cover of the districts is represented by dark-chestnut soils and their complexes with saline soils, which are characterized by a humus profile with a thickness of 40–48 cm, significant salinity, insignificant humus content (2.8–3.0%), weak structure of the arable layer.

Agricultural soil quality class determination was carried out on the basis of climatic data, their value for agricultural production, morphometric characteristics of relief, distribution of solar radiation balance, in accordance with ecological, agro-ameliorative and climatic conditions of soils.

The study of the spatial heterogeneity of the climatic conditions of the territory of the region was carried out according to the data of global climatic rasters WorldClim (http://worldclim.org) and Kherson Hydrometeorological Center. Agrochemical condition of agricultural land is determined according to the data of 296 stations of tour XI (2013–2017) of examinations of Kherson branch of the State Institution “Soils Protection Institute of Ukraine”. Assessment of soil agrochemical condition was performed for layer 0–20 cm and included the following indicators: humus (%), nitrification nitrogen (mg/kg), mobile phosphorus (mg/kg), exchangeable potassium (mg/kg) content. The residual of spatial models is determined by the distribution of standard error of calculations. The validity of spatial modeling is as follows: in terms of humus content – 92.0%, nitrification nitrogen – 85.8%, mobile phosphorus – 87.8%, exchangeable potassium – 91.4%, content (%).

The study of the ecological and ameliorative condition of soils (the groundwater level and the degree of soil salinization) was determined according to the data of Kakhovka hydrogeological and ameliorative expedition in Kherson region in 1966–2019.

Evaluation of soil and climatic potential was conducted using I. I. Karmanov's quality class determination model for growing a group of cereals, which occupy 57% of the agricultural land of the region, according to the formula:

$$SB = 8.2 \times V \times \frac{\sum t^{o} \geq 10^{o} \times HF}{CC + 70}, \tag{1}$$

where V is the raster of the weight coefficients of agro-groups according to I. I. Karmanov's method; $\Sigma t° \geq 10°$ is the raster of the sum of the average annual sum of active temperatures ≥10 °C; HF is the raster of the humidity factor according to M. M. Ivanov; CC is the raster of the coefficient of continentality.

The value of the coefficient of the continentality (*CC*) is calculated according to the formula:

$$CC = \frac{360(t^{o}_{\max} - t^{o}_{\min})}{\varphi + 10}, \tag{2}$$

where $t°_{max}$ is the average monthly temperature of the warmest month; $t°_{min}$ is the average monthly temperature of the coldest month; ϕ is the latitude.

Humidity factor (*HF*) is calculated according to the formula:

$$HF = P / E, \tag{3}$$

where P is the average annual precipitation, mm; E is average annual evaporation, g/cm^2.

Spatial modeling of ecological, ameliorative and climatic zonal soils quality class determination is carried out on the basis of the author's model:

$$BAL = 8.2 \times V \times \frac{(R - 9.9289) / 0.0121 \times (P + IN) \times K_K \times L \times W \times S_S}{0.94 \times R \times (CC + 70)}, \quad (4)$$

where V is the raster of correction factors corresponding to the soil type; R_s is the raster of the radiation balance on inclined surface, kcal/cm^2 per year; P is the raster of the average annual amount of precipitation during the vegetation, mm; IN is the raster of the actual annual average irrigation rate for cereals, mm; L is the latent heat of vaporization equal to 597 cal/g; CC is the raster of the coefficient of continentality; K_K is the raster of complex coefficient of agrochemical soil properties; W is the raster of groundwater level correction factors; S_S is the raster of the type of soil salinization correction factors.

The calculation of the spatial differentiation of the balance of solar radiation (R, kcal/cm^2), taking into account the unevenness of the surface, is made according to the formula:

$$R = R_0 \frac{\cos(s) \times \sin(h) + \sin(s) \times \cos(h) \times \cos(\psi_s - e)}{\sin(h)}, \quad (5)$$

where R_0 is the value of the radiation balance of the horizontal surface for each month of the year, kcal/cm^2; h is the daily average height of the sun for each month, rad; ψ is the azimuth of the projection of the normal to the slope on the horizontal plane, rad; s is the raster of slopes, rad; e is the raster of directions, rad.

The raster of the complex coefficient of soil agrochemical properties is calculated according to the statistically normalized values of the weighted average amount of microelements content in the soil layer 0–20 according to the formula:

$$K_K \quad \frac{\sum (M \ / \ M_{\max})}{}, \quad (6)$$

where M_i is value of the i microelement of soil for plant development; $M_{\max}$ is the maximum value (reference value) of the spatial sample of the *i* soil microelement; *n* is the number of soil microelements.

The groundwater level and type of soil salinization correction factors were assigned according to Tsybikdorzhiev's classification (2009) (Table 1).

Table 1. Negative ecological and ameliorative soil properties correction factors

Degree of the negative impact	Complexity group	Correlation coefficient
Bogginess		
Absent (non-boggy soil)	1	1.00
Mild (C horizon gleization with groundwater discharge in lower part of the crossover)	2	0.90
Medium (B and C horizon gleization with groundwater discharge at the depth of 75–100 cm)	3	0.80
Increased (groundwater in the soil crossover at the depth of 55–70 cm)	4	0.65
High (groundwater at the depth of 0–50 cm)	5	0.20
Extremely high (groundwater level at the soil surface)	6	0.10
Salinization		
Non-saline soils	1	1.00
Sodium-carbonate and mixed salinization:		
mild	2	0.85
medium	3	0.70
high	4	0.40
extremely high	5	0.25
Sulfate and chloride-sulfate salinization:		
mild	2	0.88
medium	3	0.75
high	4	0.45
extremely high	5	0.29
Sulfate-chloride and chloride salinization:		
mild	2	0.90
medium	3	0.72
high	4	0.48
extremely high	5	0.30

The raster of distribution of quality class points enabled to calculate spatial differentiation of regulatory and monetary valuation of agricultural land conducted separately by type of agricultural land: arable land, perennial plants, hayfield, pastures, fallows.

Regulatory and monetary valuation of agricultural land is determined in accordance with the standard of capitalized rental income in the areas of Kherson region (Table 2, see p. 101).

The scale of regulatory monetary valuation (*RMV*) of agro-production groups of agricultural soils was carried out according to the formula:

$$RMV = \frac{SCRI \times B_{NAA}}{\bar{B}_R}, \qquad (7)$$

where $SCRI$ is the standard of capitalized rental income of the respective agricultural land of the natural agricultural area of the region, UAH/ha; B_{NAA} is the soil quality class point of the agro-production group of soils of the respective agricultural land of the natural agricultural area; $\bar{B}_R$ is the quality class point of soils of the respective agricultural land of the natural agricultural area of the region.

Raster of regulatory and monetary valuation is the basis for determining the real value of agricultural land plots, taking into account their condition and differentiation of tax per hectare of agricultural land. In this regard, spatial simulation was performed using the methods of geostatistics and map algebra of ArcGIS 10.1 software.

RESULTS AND DISCUSSION

The total area of Kherson region makes 2,846.1 thousand hectares (Fig. 2, see p. 102), of agricultural land – 1,971.0 (69.25%) thousand hectares, including arable land – 1,777.6 thousand hectares (90.2%).

During the 1980–2020, sustainable use of agricultural land with minor increase of 0.3% was observed. The region concentrates 20% of the irrigated lands of Ukraine; their area is about

426.8 thous. Ha (21.65%). According to the recent data of the State Agency for Water Resources of Ukraine (2019), irrigated land used in irrigation mode make 312.4 thous. Ha (73.2%), while

Table 2. Standards of capitalized rental income on agricultural lands of natural agricultural areas of Kherson region

Name of the natural agricultural area, area code	**Areas**	**Standards of capitalized rental income, $\frac{UAH}{USD}$**			
		Arable land, fallows	**Perennial plants**	**Hayfield**	**Pastures**
Beryslavsky	Beryslavsky	$\frac{27,954.34}{1,118.17}$	$\frac{44,201.45}{1,768.06}$	$\frac{22,859.53}{914.38}$	$\frac{22,859.53}{914.38}$
	Velykooleksandrivsky				
	Vysokopilsky				
	Novovorontsovsky				
Nyzhnosirogozky	Velykolepetysky	$\frac{27,954.34}{1,118.17}$	$\frac{49,904.86}{1,996.19}$	$\frac{7,730.17}{309.21}$	
	Verkhnorohachytsky				
	Hornostaivsky				
	Nyzhnosirogozky				
Belozersky	Belozersky	$\frac{25,804.01}{1,032.16}$	$\frac{49,904.86}{1,996.19}$	$\frac{8,696.44}{347.86}$	
	Kherson city				
Oleshkovsky	Holoprystansky	$\frac{18,636.23}{745.45}$	$\frac{17,110.24}{684.41}$	$\frac{3,140.38}{125.62}$	
	Oleshkovsky				
	Kakhovsky				
	Nova Kakhovka city				
Skadovsky	Skadovsky	$\frac{35,646.33}{1,425.85}$	$\frac{35,646.33}{1,425.85}$	$\frac{4,589.79}{183.59}$	
Chaplinsky	Chaplinsky	$\frac{22,936.89}{917.48}$	$\frac{35,646.33}{1,425.85}$	$\frac{5,556.06}{222.24}$	
	Kalanchatsky				
Genichesky	Genichesky	$\frac{18,636.23}{745.45}$	$\frac{35,646.33}{1,425.85}$	$\frac{4,106.65}{164.27}$	
	Novotroitsky				
	Ivanivsky				

114.4 thous. Ha (26.8%) remain unused. The area of rice irrigation systems is 8.1 thous. ha (Breus et al., 2019). The main types of soil in Kherson region are southern chernozem occupying 43.7% of the total area of agricultural land and dark chestnut soils – 30.7% (Fig. 3, *a* (see p. 103)).

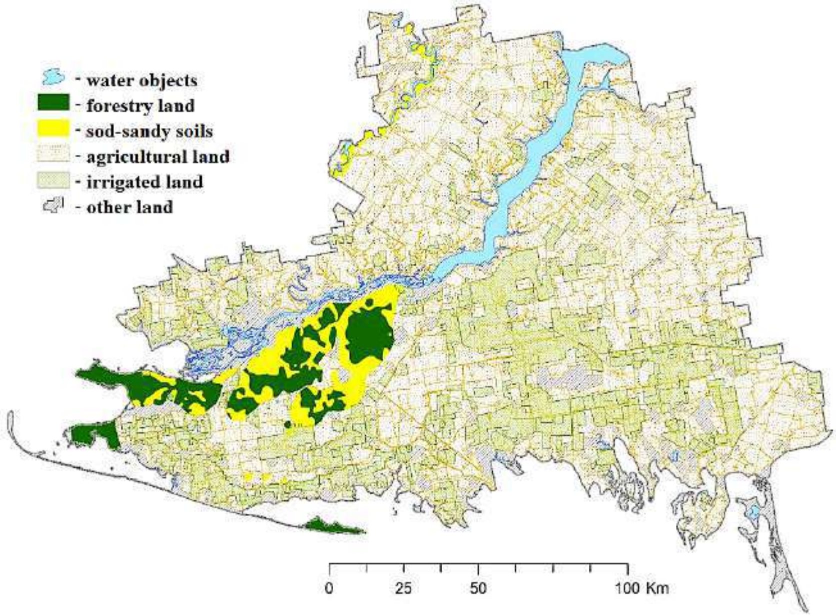
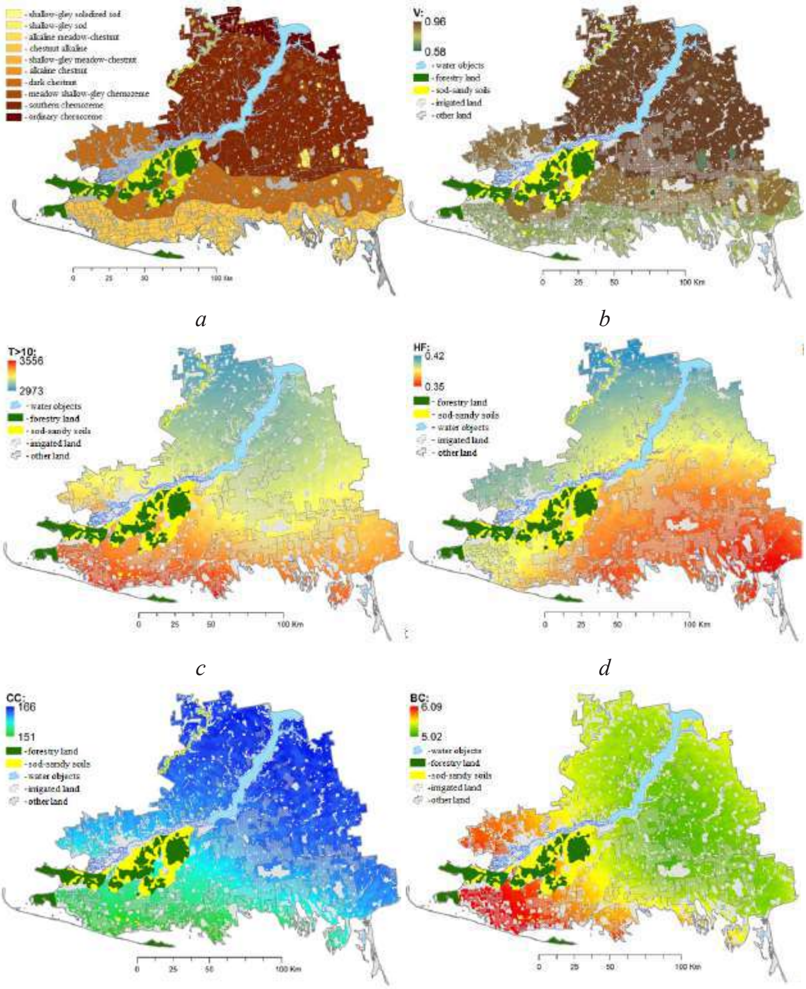


Figure 2. Agricultural development of the territory of Kherson region

To determine the spatial differentiation of soil and climatic quality class point of soils according to I. I. Karmanov's method, each agro-group is assigned a weight coefficient of agricultural value of soils, which varies from 0.58 (within sod-sandy boundaries) to 0.96 (ordinary chernozem). The resulting raster (Fig. 3, *b* (see p. 103)) of coefficients distribution provides for the possibilities to specify the quality class point for soil type according to the yield of agricultural crops.

Spatial differentiation of the bioclimatic potential of the territory is caused by the distribution of natural humidity, solar radiation and



a *b*

c *d*

e *f*

Figure 3. Spatial distribution of components of soil and climatic soil quality class in the territory of Kherson region:
a – types of soils; *b* – coefficient of the total indicator of soil properties (*V*);
c – average annual air temperature above 10 °C;
d – Ivanov's humidity factor (*HF*); *e* – coefficient of continentality (*CC*);
f – distribution of climatic quality class (*BC*)

air temperature above 10 °C (Table 3), which influences the processes of biochemical accumulation and migration of substances in the soil.

The sum of active temperatures above 10 °C decreases from the south to the north of the territory of Kherson region from 3,556 °C to 2,973 °C (Fig. 3, *c* (see p. 103)). The humidity factor (*HF*), calculated according to M. M. Ivanov's method, characterizes the ratio of annual precipitation to annual evaporation from the relief surface and characterizes the supply of plants with water.

Table 3. Statistical characteristics distribution of the properties of bioclimatic indicators in the territory of the Kherson region

Bioclimatic indicators	MIN	MAX	RANGE	MEAN	STD
Active temperatures above 10 °C	2,972.8	3,555.8	583.0	3,252.7	129.1
Humidity factor (*HF*)	0.354	0.422	0.068	0.383	0.015
Coefficient of continentality (*CC*)	151.63	166.18	14.55	161.25	3.28
Climatic quality class (*BC*)	5.02	6.09	1.06	5.37	0.22

The value of *HF* in the region decreases from southeast to northwest from 0.35 to 0.42 (Fig. 3, *d* (see p. 103)), which causes the functioning of landscape ecosystems in extremely arid and arid climatic conditions. Steppe soils belong to the area of risky agriculture with a low rate of soil formation and significant manifestations of deflationary processes.

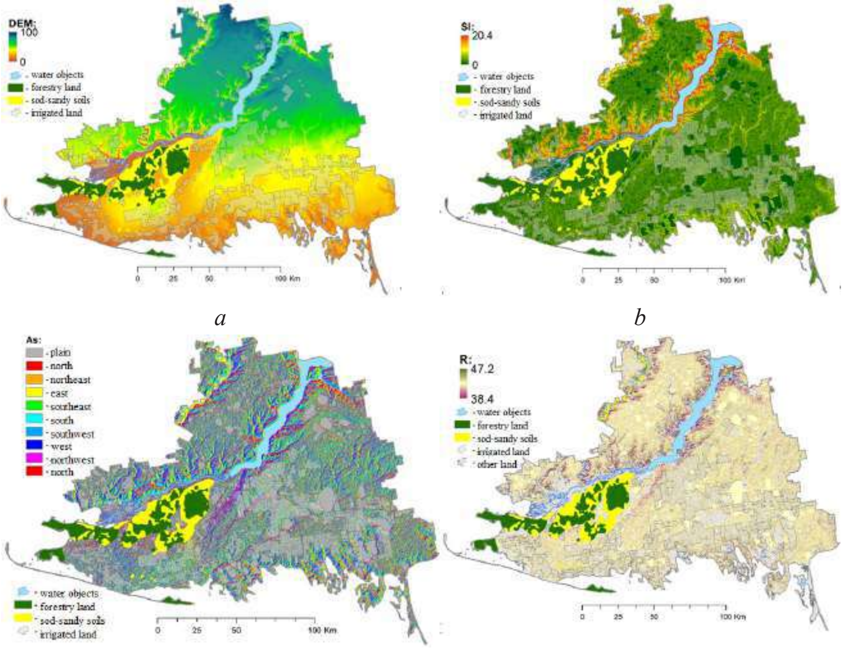
The coefficient of climate continentality (CC) has the reverse value. At high values, it is characterized by high amplitude of air temperature and low precipitation level. On the territory of the region, the CC value varies between 151–166 (Fig. 3, *e* (see p. 103)). The highest value of the quality class point (6.09) is typical for the southwestern territory of the region with chestnut and sod-sandy soils (Fig. 3, *f* (see p. 103)). More than 50% of the landscapes are provided with climatic quality class within 5.02–5.55 points for ordinary chernozem soils.

The relief of the territory is one of the main characteristics of spatial extrapolation of climatic conditions, soil type and fertility. Application of these relief data and its morphometric characteristics (steepness of slopes and their direction) significantly increases the reliability of estimates of the state of agricultural landscapes, microclimate conditions and distribution balance of solar radiation and zonal soils quality class determination. The relief affects the agro-landscape water supply, which is determined by the heterogeneity of precipitation redistribution and moisture loss due to evaporation from the slopes of different steepness and direction. High solar radiation of the southern slopes leads to intense snow melting, water erosion of soils and reduced melt water uptake by up to 20–70% (Dudiak et al., 2019). In particular, the absorption of melt water on the slopes of the northern direction is 70–100%. In the mixed forests area with excessive and sufficient water, the redistribution of spring precipitation is: on the southern slopes – 25–30%, on the northern slopes – 30–40%, at the foot – up to 100%. In forest-steppe and steppe areas, precipitation redistribution in spring is: on the southern slopes – 15–25%, on the northern – 25–30%.

Digital elevation model was created on the basis of sonar data of the shuttle radar topography mission (SRTM) with a spatial resolution of 30 × 30 m (Fig. 4, *a* (see p. 106)) and its morphometric analysis was conducted – the spatial differentiation of slope steepness (Fig. 4, *b* (see p. 106)) and direction (Fig. 4, *c* (see p. 106)) was determined. The slope steepness values in Kherson region range from 0° in the plain to 20.4° in the river coast territories. Territories located on a plateau make up 13.3% of arable land, territories with slope steepness from 0° to 1° make up 78.3%, within 1°–2° – 6.6%, from 2°–3° – 1.3%, 3° and more – 0.5%.

One of the main morphometric indicators of the slopes is their direction (Fig. 4, *c*), which characterizes heat supply due to solar energy, which affects most types of economic activity, erosion and soil formation processes. On agricultural land of Kherson region, areas with different direction of slopes are distributed from 5.6% (northern) to 12.4% (western). Soils on the slopes of the northern direction occupy 24.1% of arable land and are characterized by an increased degree of water supply. Soils on slopes of southern direction occupy 35.2% of arable land; they are prone to more intensive erosion as a result of snowmelt and spring showers.

It is established that the value of the solar radiation balance (*R*, kcal/cm^2), depending on the morphometric characteristics of the relief in the territory of the region varies within 38.4–47.2 kcal/cm^2 (Fig. 4, *d*). Solar radiation balance increases the soil quality class point when determining the sum of active temperatures, and lowers it when determining the humidity coefficient.



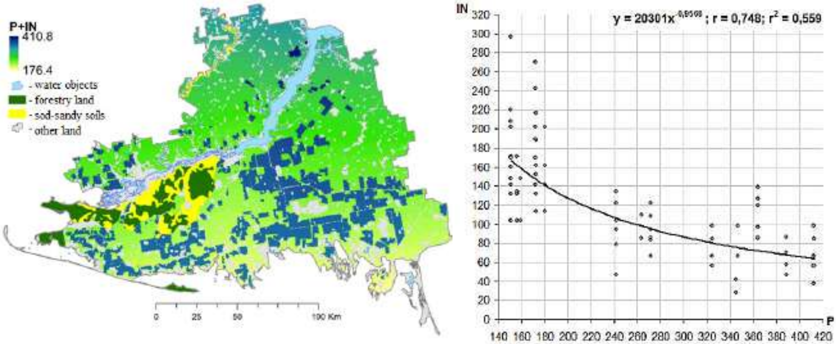
a *b*

c *d*

Figure 4. Morphometric characteristics of the territory of Kherson region:
a – digital elevation model (*DEM*), m; *b* – slope steepness (*Sl*), degree;
c – slopes direction (*As*); *d* – surface radiation balance (*R*), kcal/cm^2 per year

In 1966–2019, during vegetation periods, positive trend-cyclical pattern of temperature regime change was observed. Two time periods of air temperature formation are determined (*T*, °C): period I (1966–1996) – stable with average value $\overline{T} = 16.54 \pm 0.16$, variation level $V = 5.4\%$ and slight trend of $\mathrm{T} = -0.168Ln(t) + 16.96$; $r = 0.16$ type; period II (1997–2019) – rapid rise in the value of the average vegetation air temperature by 1.6 °C with an average value $\bar{T} = 18.12 \pm 0.31$, variation level $V = 7.4\%$ and a significant trend component $\mathrm{T} = 16.403e^{0.0102t}$; $r = 0.76$.

The main component of energy expenditure for soil formation and formation of soil quality class points is the precipitation sum (P, mm). On irrigation and amelioration lands, the total water supply is additionally determined by the irrigation rate (IN, mm). Between 1966 and 2019, the average value of the total precipitation in Kherson region from south to north varied from 155 to 330 mm during the vegetation. In particular, the total water supply ($P + IN$, mm) on the irrigated lands was 345–410 mm (Fig. 5, *a*), which led to an increase in energy expenditures for soil formation compared to the non-irrigated lands by 335 MJ/m^2 (up to 850 MJ/m^2) and increase in the irrigated soil quality class. The total amount of energy expenditure for soil formation in the region varied from 265–765 MJ/m^2 on non-irrigated land to 790–910 MJ/m^2 on irrigated land during the vegetation. Annual cycle of natural water supply necessitates the adjustment of the irrigation standard in order to obtain stable yields of agricultural crops (Fig. 5, *b*).



a *b*

Figure 5. Total water supply ($P + IN$, mm*)* of agricultural land of Kherson region during the vegetation in 1966–2019 (*a*) and dependence of spatiotemporal differentiation of IN and P (*b*)

The main soils quality class index is their agrochemical condition, which is characterized by major components of macro-nutrition of agricultural crops – humus, nitrification nitrogen, exchangeable potassium and mobile phosphorus (Table 4).

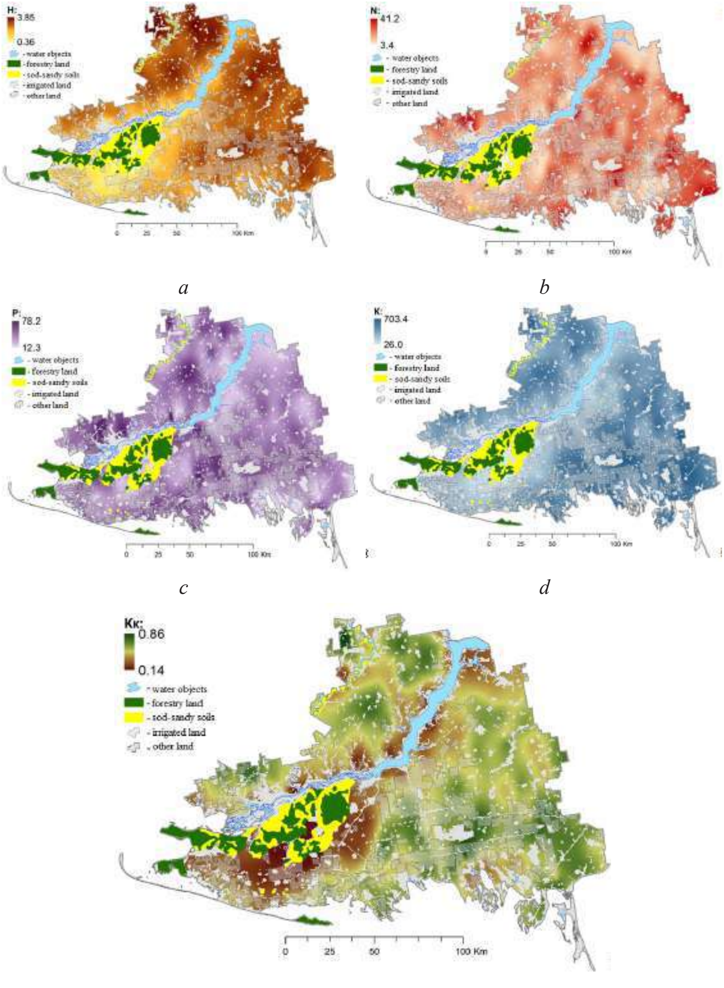
Table 4. Statistical characteristics distribution of the properties of agrochemical indicators in the territory of the Kherson region

Agrochemical indicators	MIN	MAX	RANGE	MEAN	STD
Humus (*H*)	0.36	3.85	3.49	2.44	0.64
Nitrification nitrogen (*N*)	3.39	41.23	37.84	20.52	5.05
Exchangeable potassium (*K*)	25.99	703.42	677.42	401.84	134.44
Mobile phosphorus (*P*)	12.29	78.23	65.94	41.27	9.73

The soil cover of Kherson region is characterized by low-humus soils with humus content within 0.30–3.85% (Fig. 6, *a* (see p. 109)). Spatial heterogeneity of humus content is determined by the complexity of the structure of the soil, which is first of all determined by zonal factors of soil formation and heterogeneity of hydrothermal conditions, second of all – by the development of gley processes in groundwater due to their sporadic excessive water saturation by melt and rain water, third of all – by intense process of alkalinization and salinization in the shallow groundwater.

Features of the soil cover determine the initial humus content, which, as a result of economic activity, is undergoing dynamic changes. This is determined by farming intensity and standards within land plots (crop rotation fields) and land use. In irrigation conditions, humus content in different soil types of the region (layer 0–20 cm) on average is 0.1–0.5% less than that for non-irrigated lands. This is determined by the intensity and technological features of irrigated meliorations (water quality, irrigation standards, crop rotations, etc.).

Dehumification of soils is explained by increased mineralization of organic matter as a result of intensive treatment and imbalance of production and soil formation processes, insufficient intake of crop residues and organic fertilizers by arable horizon, increase in the proportion of tilled crops, reduction in the proportion of



a *b*

c *d*

e

Figure 6. Agrochemical condition of agricultural lands of Kherson region (2013–2017):

a – humus content (*H*), %; *b* – nitrogen content by soil nitrification capacity (*N*), mg/kg of soil; *c* – mobile phosphorus content (*P*), mg/kg soil; *d* – radiation content of exchangeable potassium (*K*), mg/kg of soil; *e* – raster of the correction factor of the soil quality class point by agrochemical properties (K_K)

perennial grasses in field crop rotations, dominating use of mineral fertilizers (especially physiologically acid forms), insufficient use of crop residues as organic fertilizers, stubble burning, often burning of residual straw, water erosion manifestations, including irrigation erosion, and soil deflation, as well as the result of a long-lasting irrigation (Lisetskii et al., 2017).

Intensification of the negative degradation processes of the soil cover caused decrease of the humus content in the steppe soils by 0.36% over the last 50 years (from 2.56% to 2.20%). At the same time, high spatial heterogeneity of humus distribution is observed on the territories of irrigated dark chestnut soils of the southern part of Kherson region (59.3% of irrigation area). Thus, there takes place a specific degradation of soils, which is the result of excess irrigation of agricultural land.

Humus content in the soil (Table 5), which meets quality gradations of medium and increased content (>2.1%), is typical for 72.5% of the agricultural land in Kherson region.

Table 5. Distribution of humus content in soils of agricultural lands of the region

Humus content, %		**Distribution of agricultural lands**	
		thous. ha	**%**
extremely low	<1.10	124.4	6.3
low	1.10–2.09	418.3	21.2
medium	2.10–3.09	1,182.3	60.0
increased	3.10–4.09	246.0	12.5
Total		1,971.0	100.0

The highest weighted average value of humus content of 3.04% was recorded in the ordinary chernozem soil located in the northern part of the region, the lowest humus content was found in sod-sandy soils – 0.88%. Nitrogen is an important biological element and plays an exceptional role in the life of plants. In 1998–2017, there was a negative trend formation of nitrogen content in the arable layer (0–20 cm) of soil in Kherson region ($NO_3 = -0.053t^2 + 0.966t + 16.74$; $R^2 = 0.24$), which has led to decrease of its content by 17.0%

(from 23.0 mg/kg to 19.1 mg/kg). Nitrogen content in soils (Fig. 6, *b* (see p. 109), Table 6), which meets quality gradations from medium to increased content (>21.0 mg/kg), characterizes 47.4% of the agricultural land area. The highest share of agricultural land with medium-to-increased nitrogen content with nitrification capacity was noted in the central and eastern parts of the region.

Table 6. Distribution of nitrification nitrogen content in soils of agricultural lands of the region

Nitrification nitrogen content, mg/kg		**Distribution of agricultural lands**	
		thous. ha	**%**
extremely low	<10.0	64.0	3.2
low	11.0–20.0	972.1	49.3
medium	21.0–30.0	881.5	44.7
increased	31.0–45.0	53.4	2.7
Total		1,971.0	100.0

In addition, phosphorus is an important and scarce element of plant nutrition. It is a compound of nucleoproteins, sugar-phosphates, phosphatides and other compounds, is actively involved in metabolism and protein synthesis processes, determines the energy of cells, affects plants growth. Over the last 50 years, the content of mobile phosphorus in the soil layer of 0–20 cm in Kherson region has decreased by 34.17% (from 62.0 mg/kg to 40.8 mg/kg) and has a negative tendency to decrease in its content: $T = -10.59 \times \mathrm{Ln}(t) + 62.31$; $R^2 = 0.98$. The content of mobile phosphorus in soils (Fig. 6, *c* (see p. 109), Table 7 (see p. 112)), which meets quality gradations from increased to extremely high content (>31.0 mg/kg), is typical for 87.3% of agricultural land. The vast majority of the region's lands (56.2%), mainly in irrigated areas, are characterized by high and extremely high levels of mobile phosphorus.

There has been determined the presence of different forms of potassium in the soil related to the primary and secondary minerals, as well as features of their transformation. Over the past 50 years, exchangeable potassium content in the layer of soil 0–20 cm of Kherson region decreased by 18% (from 442.4 mg/kg to 363.8 mg/kg) and keeps the downward trend: $T = -36.87 \times \mathrm{Ln}(t) + 437.75$; $R^2 = 0.97$. The spatiotemporal heterogeneity of the decrease in potassium in soils from 50 mg/kg to 210 mg/kg (from 10% to 50%) is determined by the absence of regular, uniform flow of mineral fertilizers, the manifestation of water erosion, including irrigational erosion, and soil deflation, as well as the result of long-lasting irrigation. The content of exchangeable potassium in soils (Fig. 6, *d* (see p. 109), Table 8), which meets quality gradations from medium to extremely high content (>200 mg/kg), is typical for 85.8% of agricultural land. High content of exchangeable potassium in excess of 400 mg/kg of soil is recorded in the northwestern and southeastern parts of the region.

To clarify the spatial differentiation of steppe soils quality class point, the raster of complex factor of agrochemical properties of soil (K_K) was created. It is found that the value of K_K varies

Table 7. Distribution of mobile phosphorus content in soils of agricultural lands of the region

Mobile phosphorus content, mg/kg		**Distribution of agricultural lands**	
		thous. ha	**%**
medium	16.0–30.0	250.0	12.7
increased	31.0–45.0	1,064.4	54.0
high	46.0–60.0	599.7	30.4
extremely high	>60.0	56.9	2.9
Total		1,971.0	100.0

Table 8. Distribution of exchangeable potassium content in soils of agricultural lands of the region

Exchangeable potassium content, mg/kg		**Distribution of agricultural lands**	
		thous. ha	**%**
extremely low	<100	70.6	3.6
low	101–200	211.2	10.7
medium	201–300	459.8	23.3
increased	301–400	572.6	29.1
high	401–600	596.3	30.3
extremely high	>600	60.5	3.1
Total		1,971.0	100.0

from 0.14 to 0.86 (Fig. 6, *e*, see p. 109). The most productive soils in terms of agrochemical properties are agricultural lands located on the ordinary chernozem soil in the northern part of the region and on southern chernozem of the central-eastern and western parts. The least productive soils for growing agricultural crops are lands located in the southwestern part of the region on dark chestnut and chestnut alkaline soils.

Additional components for determining the soil quality class point in the irrigation area are indicators of the ecological and ameliorative condition of the land – the groundwater level and the degree of soil salinization, the negative manifestations of which affect the level of agricultural crop failure. Depending on the groundwater levels (GWL) and the degree of soil salinization, agricultural crop losses reach up to 60%. Therefore, it is suggested to include correction factors in the methodology of calculation of soil quality class in the irrigation area. They shall take into account the degree of deterioration of the ecological and ameliorative condition of irrigated and adjacent lands and reduction of the soil quality class level.

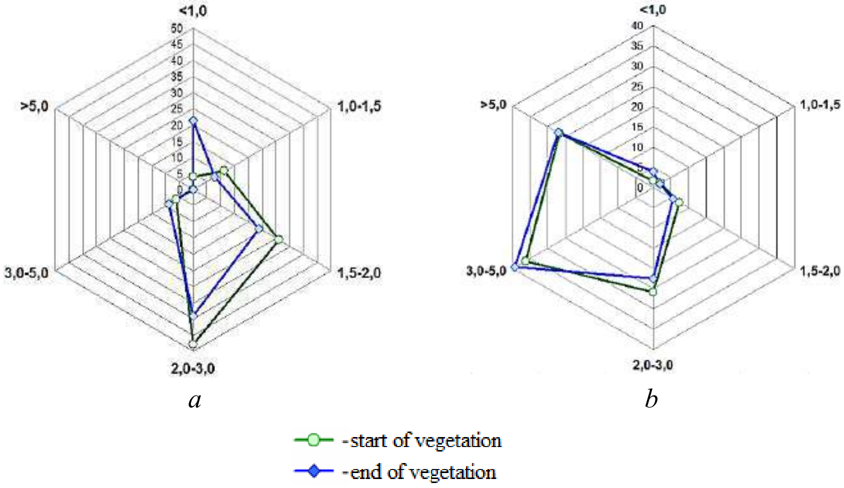
As a result of spatiotemporal studies, there has been observed a systematic flooding of irrigated lands and adjacent territories in the last 20 years (Fig. 7, see p. 114).

Changes in groundwater levels depend on the sum of precipitation, mode of irrigation, infiltration processes of irrigation channels and the efficiency of collector and drainage systems. The most regular flooding (GWL < 2 m) occurs on the territories occupied by rice systems (Fig. 7, *a*, see p. 114): at the start of vegetation – 46.3% and at the end of vegetation – 73.3%. Areas without rice systems are flooded by 11.2% (Fig. 7, *b*, see p. 114).

As a result of spatial modeling, systematic flooding of agricultural land of Kherson region occupied by rice is observed (Fig. 8, *a*, see p. 115). Flooding takes place along the edges of the irrigation areas at the lowest geodetic marks, at the depth of groundwater, in areas located along the irrigation canals, coastal areas of the Black and the Azov seas. Territories with GWL of less than 2 m make up 4.7% of agricultural land, from 2 to 3 m – 10.9%, within 3–5 m – 22.3%, 5 m and more – 62%. According to the group of bogginess complexion, the soils of the territory of the region were assigned corresponding correction factors from 0.8 (flooded territories) to 1.0 (non-flooded territories) and the raster of negative impact of GWL on soil fertility properties was created (Fig. 8, *b*, see p. 115).

Alkalinization and re-salinization of agricultural land occurs in natural conditions of arid regions due to excess irrigation, low natural outflow of mineralized groundwater and poor drainage and overflow network of irrigation system, resulting in capillary rising of brackish and saline water, degradation of soil and increase in space concentrations of alkaline soils. They have low fertility rates and are poorly suitable for growing most agricultural crops by their agrophysical and chemical properties.

According to salt imaging and studies at the saline stations of Kakhovka hydrogeological and ameliorative expedition of Kherson region, an appropriate interpretative map was created and the spatial distribution of land by degree of salinization was determined (Fig. 8, *c*, see p. 115).

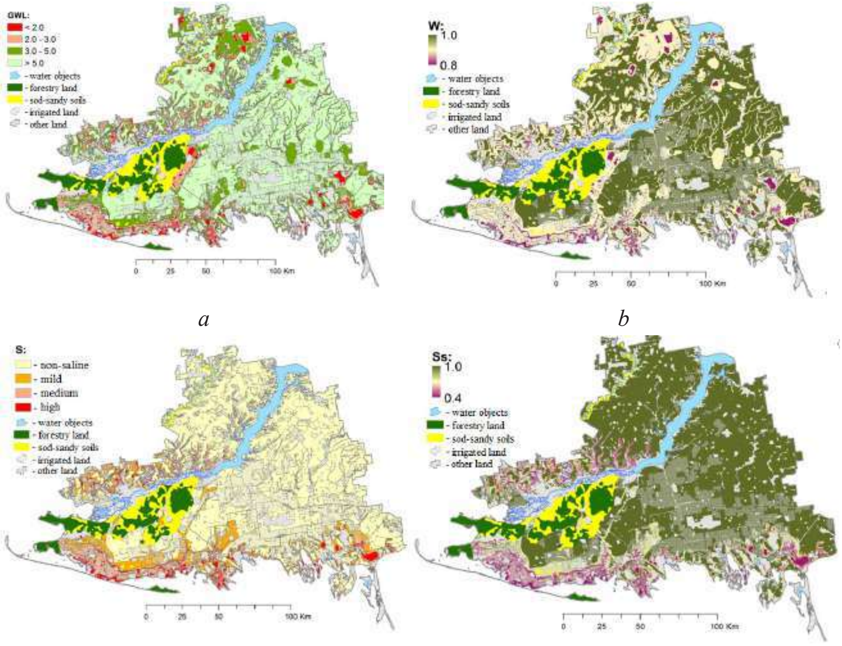


a *b*

Figure 7. Distribution of irrigated and adjacent lands in Kherson region for the period 2000–2019:
a – rice systems; *b* – non-rice systems

About 80% of the territory of the agricultural lands of the region are non-saline and non-saline with soda content soils; 9.6% are saline, 7.0% are medium saline and 3.4% are highly saline soils. The main part of the lands with manifestations of soil salinization is located on the irrigated lands of the southern part of the region. According to the group of soil salinization complexity, the soils of the territory of the region were assigned corresponding correction factors from 0.4 (highly saline) to 1.0 (non-saline) and the raster of negative impact of salinity level on soil fertility properties was created (Fig. 8, *d*).

According to the abovementioned characteristics of the study of soil fertility properties, there were created the rasters

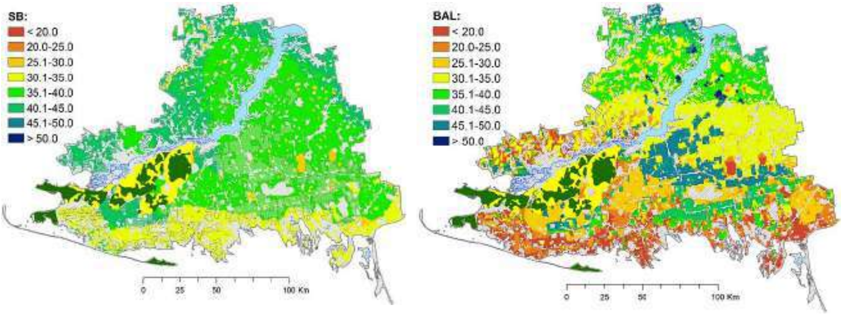


a *b*

c *d*

Figure 8. Spatial differentiation of ecological and ameliorative condition of soils of Kherson region:
a – groundwater level (*GWL*), m; *b* – groundwater level correction factors (*W*); *c* – degree of soil salinization (*S*); *d* – soil salinity correction factors (*Ss*)

of spatial distribution of steppe soils quality class by two methods of calculation: soil and climatic quality class determination by I. I. Karmanov, where the value of quality class point varies from 25 to 46 points (Fig. 9, *a*); modified model of ecological, agro-ameliorative and climatic soil quality class determination, where the value of quality class point varies from 6 to 59 points (Fig. 9, *b*).



a *b*

Figure 9. Spatial differentiation of quality class of soils of Kherson region for grain crops cultivation:
a – soil and climatic quality class determination (*SB*, *formula 1*), point;
b – ecological, agro-ameliorative and climatic soil quality class determination (*BAL*, *formula 4*), point

Spatial division of areas using two methods of soil quality class determination is given in Table 9 (see p. 117). The point unit is equal to the unit of potential crop yield (c/ha). Application of the modified author's method allows to objectively carry out soil quality class determination for grain crops cultivation, taking into account additional parameters of modern agrochemical soil condition, morphometric characteristics of relief, distribution of solar radiation balance, irrigation rates and ecological and ameliorative soil condition.

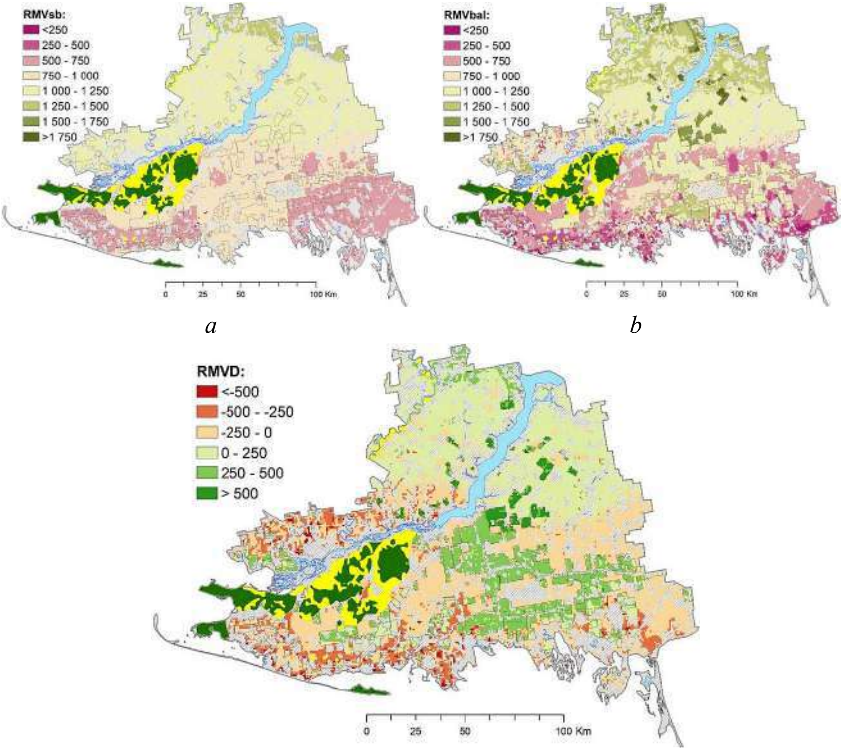
Comparison of raster models of soil quality class point differentiation gives an opportunity to reliably establish the regulatory and monetary valuation and to objectively determine the amount of tax in the steppe soils irrigation zone.

Table 9. Distribution of agricultural land of Kherson region by soil quality class point

Point	**I. I. Karmanov's soil and climatic quality class determination (Method 1)**		**Modified model of ecological, agro-ameliorative and climatic soil quality class determination (Method 2)**		**M2–M1, ± %**
	thous. ha	**%**	**thous. ha**	**%**	
<20	3.7	0.2	227.5	11.5	+11.3
20–25	9.5	0.5	219.4	11.1	+10.6
25–30	39.4	2.0	319.5	16.2	+14.2
30–35	331.4	16.8	518.2	26.3	+9.5
35–40	1,125.3	57.1	310.9	15.8	−41.3
40–45	461.6	23.4	162.5	8.2	−15.2
45–50	—	—	203.7	10.3	+10.3
>50	—	—	9.4	0.5	+0.5
Total	1,971.0	100	1,971.0	100	—

Applying the standard of capitalized rental income from arable land of natural agricultural area of the region, spatial differentiation of regulatory and monetary valuation of agricultural land on irrigated and non-irrigated steppe soils was developed on the basis of *SB* and *BAL* rasters. The value of the regulatory and monetary valuation of agricultural land in Kherson region based on soil and climatic conditions (*RMVsb*, Fig. 10, *a*, see p. 118) varies within USD 490 (dark chestnut and chestnut alkaline soil) and USD 1,360 per 1 hectare (ordinary chernozem soil); based on ecological, agro-ameliorative and climatic conditions (*RMVbal*, Fig. 10, *b*, see p. 118) – from USD 145 (degraded and highly saline chestnut soils) up to USD 2,060 per hectare (irrigated southern chernozeme soils). The spatial differentiation of changes in the regulatory and monetary valuation of agricultural lands depending on the method of soil quality class determination is presented in Fig. 10, *c* (see p. 118).

According to the regulatory and monetary valuation, the total value of agricultural land in Kherson region according to *RMVsb* model-makes USD 26.46 mln., according to *RMVbal* model – USD 29.91 mln.



a *b*

c

Figure 10. Spatial differentiation of regulatory and monetary valuation of agricultural land (RMV) on the territory of Kherson region:
a – RMV using soil and climatic quality class determination (*RMVsb*), USD; *b* – RMV using ecological, agro-ameliorative and climatic quality class determination (*RMVbal*), USD; *c* – difference “*RMVbal – RMVsb*”, USD

To increase the information content and to define the quality class point in order to conduct regulatory and monetary valuation of land in the steppe soils irrigation zone, it is necessary to introduce geo-informational and analytical system for soils monitoring using official data of relevant research government agencies and satellite images, to develop a complex of ameliorative measures to improve soils fertility properties. The system of spatial differentiation of soil protective measures should include: organizational and economic ameliorative measures – creation of a system of soil-protective crop rotations, mosaic structure of lands, conservation of degraded lands, etc.; hydro-ameliorative measures – sustainable irrigation, erosion prevention ponds, water protection areas, reconstruction and modernization of irrigation and collector and drainage systems etc.; agro-ameliorative measures – limitation of the use of heavy tillage machinery, creation of buffer strips of perennial grasses, soil protection technologies, reduction of the amounts of pesticide application, cross plowing of slopes, etc.; forest-ameliorative measures – field protection, drain regulation and spur forest strips; continuous afforestation of slopes etc.

CONCLUSIONS

There has been carried out comparison of I. I. Karmanov's methodology of soil and climatic quality class determination and author's modified methodology of ecological, agro-ameliorative and climatic soils quality class determination. The research was conducted on the example of the territory of Kherson region of Ukraine. Approbation of the author's methodology and the results obtained for the steppe zone soils have ensured objective spatial differentiation of regulatory and monetary valuation of agricultural land in irrigation area. Raster models were developed and spatial distribution patterns of soil quality class determination were established. In particular, the components of soils quality class include total index of soil properties, moisture coefficient, coefficient of climate continentality, average annual sum of active temperatures over 10 °C, differentiation of solar radiation balance, average annual sum of precipitation and irrigation rate during the vegetation, indicators of agrochemical soil properties, groundwater level and soil salinization type. Rasters of spatial distribution of steppe soil quality class were created using two calculation methods. It is established that, according to the results of I. I. Karmanov's soil and climatic quality class determination, the value of the class point varies from 25 to 46 points; the regulatory and monetary value of agricultural land varies from USD 490 per 1 ha for dark chestnut and chestnut alkaline soils up to USD 1,360 per ha for ordinary chernozem. It is established that, according to the results of ecological, agro-ameliorative and climatic soils quality class determination, the value of the class point varies from 6 to 59 points; the regulatory and monetary value of agricultural land varies from USD 145 per 1 ha for degraded and highly saline chestnut soils up to USD 2,060 per ha for irrigated southern chernozem. The suggested author's advanced methodology of soils quality class calculation is of multiple purpose, intended to be used for different physiographic conditions of land use. It increases the information content and the objectivity when determining ecological and agro-ameliorative condition of agricultural land. It improves the process of zonal soils quality class determination, increases the objectivity of regulatory and monetary valuation and tax rate on the use of agricultural land. This enables to substantiate the spatial differentiation of soil protection measures, the need for state and regional grants for implementation of projects for sustainable land use. This will ensure zonal adjustment of irrigation standards aimed at increasing yield, saving irrigation water and reducing the profile of soil degradation in irrigated areas.

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POTENTIAL OF EIGHT SPECIES OF LEGUMES FOR FUEL OIL CONTAMINATED SOIL PHYTOREMEDIATION

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INTRODUCTION

Some of the most common soil contaminants are petroleum products, this type of pollution is widespread, because various petroleum products are very commonly used around the world for various purposes. Contamination of soil with petroleum products can result directly from leaks, accidents and spills in high-traffic areas as well as at facilities involved in the refining, storage and use of petroleum products (Khan et al., 2018). It is known, that only in Europe, according to the European Environment Agency, the number of suspected contaminated soil hot spots is around 2.5 million (Report from the Commission to the European Parliament…, 2012). Meanwhile, in Lithuania, based on the data of the Lithuanian Geological Survey, about 12,000 potential sources of pollution have been identified, most of them are related to soil pollution with oil products. Unlike heavy metals, petroleum products can be broken down into environmentally harmless compounds. A variety of chemical, physical, and biological methods can be used to remediate contaminated soil, but biological ones are the most environmentally friendly (Riskuwa-Shehu et al., 2017). Implementation of leguminous plants for soil phytoremediation is very promising, because they have an ability to fix nitrogen directly from the atmosphere and stimulate the degradation of the oil products in the rhizosphere and their germination rate in petroleum hydrocarbons contaminated soil is better comparing with non-leguminous plant species (Potashev et al., 2014; Cheng et al., 2019). Moreover, this type of plant doesn't have to compete with other plants for nitrogen resources, which are often limited in contaminated and degraded soils. During the growing of leguminous plants soil is decontaminated and at the same time the soil fertility and the amount of organic matter may be increased (Yousa et al., 2022). The efficiency of legumes based phytoremediation depends on the plant species, the composition and concentration of the contaminants, soil type and other environmental factors (Osam et al., 2013).

The objective of this study was to test eight different legume species and evaluate their potential to remediate fuel oil contaminated soil.

METHODS

Eight species of leguminous plants from the *Fabacea* plant family were grown under laboratory conditions. Two different levels of fuel oil contamination in soil was chosen (2,500 mg/kg and 4,000 mg/kg). All groups of experiment were carried out in plastic pots, each pot was oval in shape and 25 cm deep. There were a total of 72 pots of tree groups. Each pot was filled approximately 4,000 grams of soil. The level of illumination on the surface of the pots reached 22,000–24,000 lumens and the duration of lighting was set 12 hours in a 24 – hour interval. The duration of the experiment was 90 days. In order to evaluate the morphometric parameters of the plants, the height of the stems was periodically measured, and the above-ground and underground plant biomass were measured at the end of the experiment. To evaluate the decomposition potential of fuel oil, the residual concentration of fuel oil in the soil was measured by gas chromatography after 45 days and at the end of the experiment (after 90 days).

RESULTS

Different species of legumes had different resistance to fuel oil, *Medicago sativa*, *Melilotus albus*, *Pisum sativum*, *Lotus corniculatus* had the highest resistance to oil products, *Lens culinaris* and *Phaseolus vulgaris had moderate resistance* while *Onobrychis visiifolia* and *Galega orientalis* were the most sensitive to fuel oil pollution Some results are shown in Fig. 1 (see p. 125).

Figure 1. Resistance of legume species to soil pollution by fuel oil (control, 2,500 mg/kg, 4,000 mg/kg)

At the end of the experiment in the group of 2,500 mg/kg initial fuel oil contamination all species showed similar results (Fig. 2 left side). The largest reduction in fuel oil concentration was recorded in pots with *Pisum sativum* (95.88%), *Galega orientalis* (95.72%) and *Lotus corniculatus* (95.60%). The lowest reduction was recorded in pot with *Lens culinaris* (86.52%). In the group of 4,000 mg/kg initial contamination some legume species were more able to decompose contaminant than others and the levels of degradation differed more than in the first group with lower soil contamination (Fig. 2 right side). The best reduction in fuel oil were obtained in pots with *Lotus corniculatus* (95.33%), *Melilotus albus* (94.68%) and

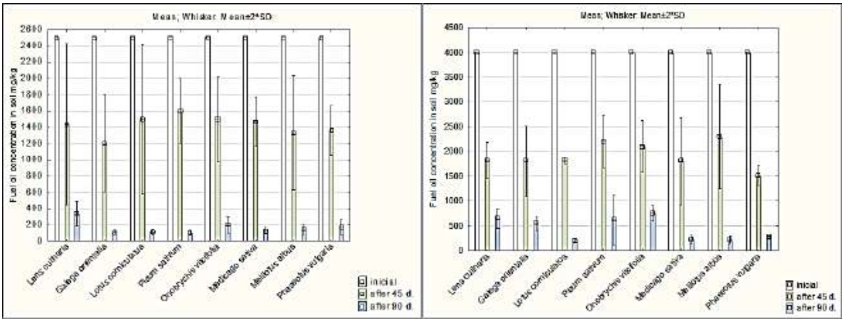

Figure 2. The potential of eight different species of legumes to decompose fuel oil in 2,500 mg/kg and 4,000 mg/kg soil contamination groups

Medicago sativa (94.43%), while the lowest decomposition potential was obtained in pots with *Onobrychis viicifolia* (81.17%) and *Lens culinaris* (83.82%).

CONCLUSIONS

Eight species of legumes were tested to evaluate the fuel oil phytoremediation efficiency. The decomposition potential of the oil product depended on the concentration level of the pollutant in the soil. At the concentration of 2,500 mg/kg, all tested species of legumes showed similar phytoremediation results. The resistance of plants to contamination as well as the intensity of fuel oil decomposition varied in the group of 4,000 mg/kg initial fuel oil contamination. The biggest reduction in fuel oil were obtained in samples with *Lotus corniculatus* (95.33%), *Melilotus albus* (94.68%) and *Medicago sativa* (94.43%), while the lowest reduction in samples with *Onobrychis viicifolia* (81.17%) and *Lens culinaris* (83.82%).

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CHANGES IN CLIMATE AND BIOCLIMATIC POTENTIAL IN THE STEPPE ZONE OF UKRAINE

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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, 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 2,800 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: $\bar{T} = 9.8\ ^{O}C$; $\bar{P} = 415$ мм . 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):

$$R = \frac{122.72T + 923.54}{41.868}, \tag{1}$$

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):

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

where R is 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):

$$F = 0.3202 \times \exp(0.003421 \times Q), \quad r = 0.96\,. \tag{3}$$

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):

$$K_h = \frac{Py}{Ey}. \tag{4}$$

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 $r^2 = 0.88$:

$$Ey = 1{,}384 - 161.6t_{\max} + 6.245t_{\max}^2 . \qquad (5)$$

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:

$$T_t, P_t = Tr_t + S_t + C_t + \varepsilon_t \,, \tag{6}$$

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; ε_{t-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:

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

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 $t+n$; $\hat{Y}_{t+p}$ – 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

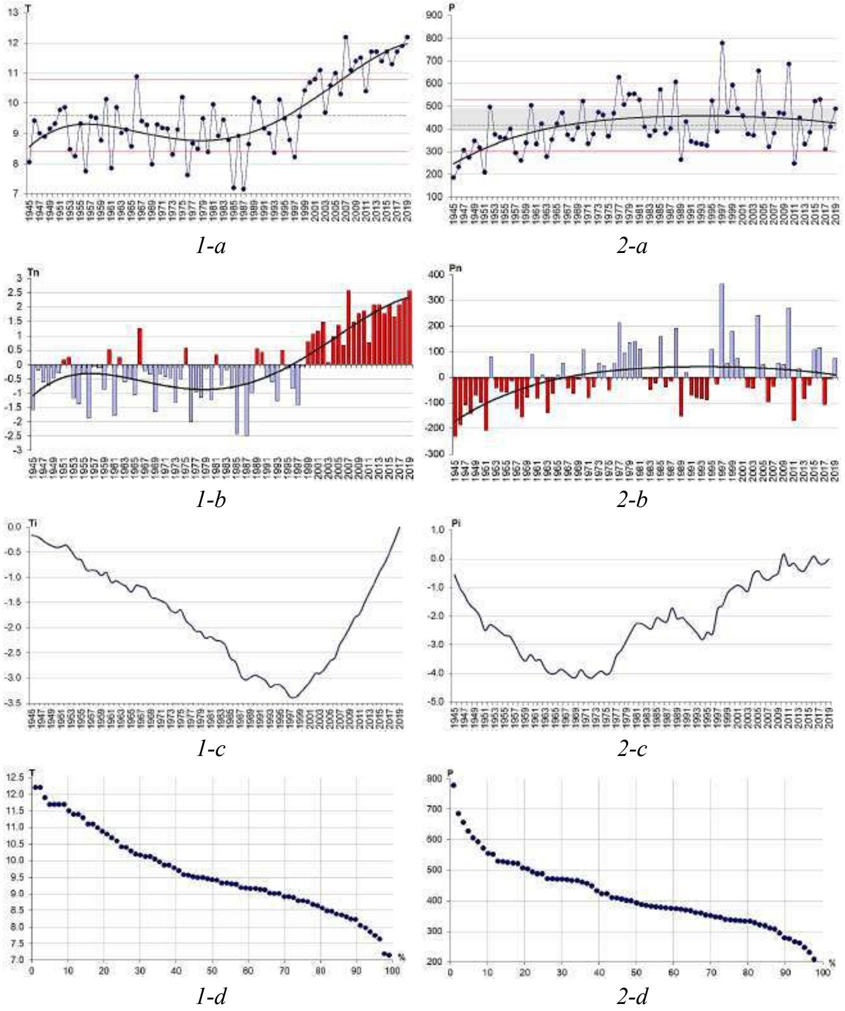
Due to extreme climatic conditions, manifestations of droughts and wind erosion, the Steppe zone of Ukraine is classified as a risky farming area. The territory is characterized by a high level of agricultural development, as of January 1, 2022, the area of agricultural land was 13,235.5 thousand hectares (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 1,324.1 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* (see p. 135)) 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* (see p. 135)), 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* (see p. 135)), 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* (see p. 135)).

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 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



1-a 2-a

1-b 2-b

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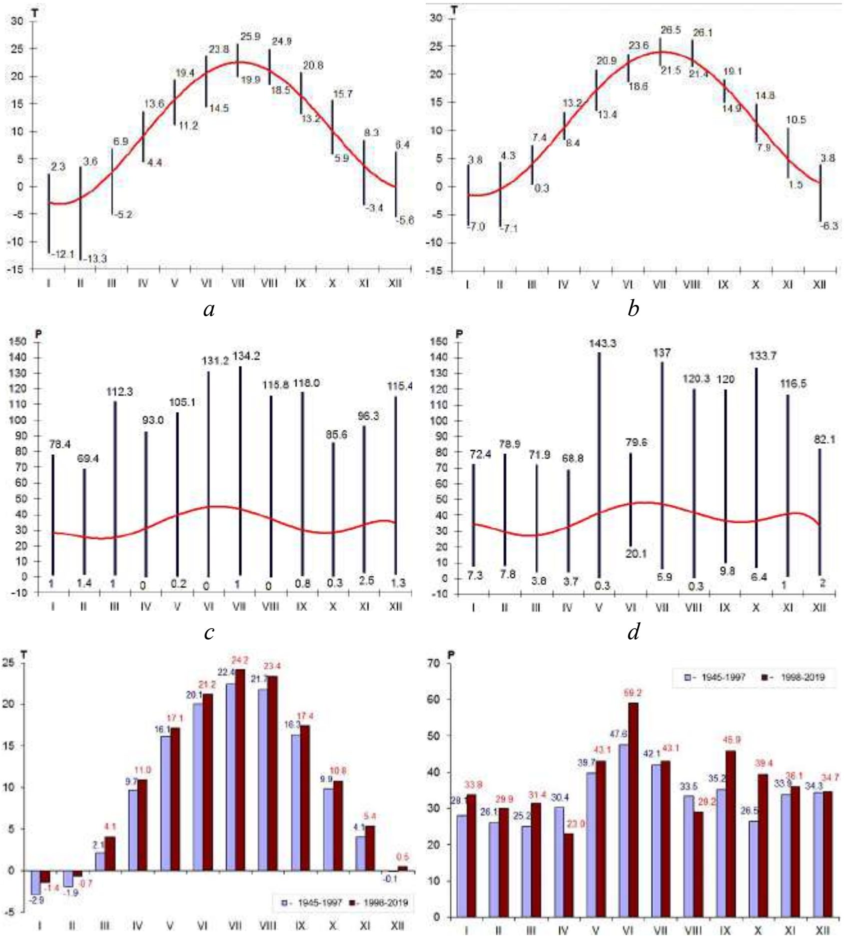
Figure 1. Characteristics of long-term climate changes in the Steppe zone of Ukraine in the period 1945–2019:

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 15.6% over 20 years. Comparative characteristics of monthly changes in minimum and maximum values are presented in Fig. 2, *a* (see p. 137) – the periods 1945–1997 and Fig. 2, *b* (see p. 137) – the period 1998–2019. Average monthly changes in the temperature conditions for two-hour slices are presented in Fig. 2, *e*.

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 mm (Fig. 1, *2-a* (see p. 135)) 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* (see p. 135)). 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* (see p. 135)). The period 1945–2019 recorded 38 years (50.7%) with dry conditions (<400 mm) of natural moisture supply (Fig. 1, *2-d* (see p. 135)), 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



a *b*

c *d*

e *f*

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

of atmospheric precipitation per year was established for the Steppe zone, the function has the following form: $y = 1{,}500.2\exp(-0.009P)$, $r^2 = 0.76$. 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: $y = -0{,}1649P + 124.4$, $r^2 = 0.58$.

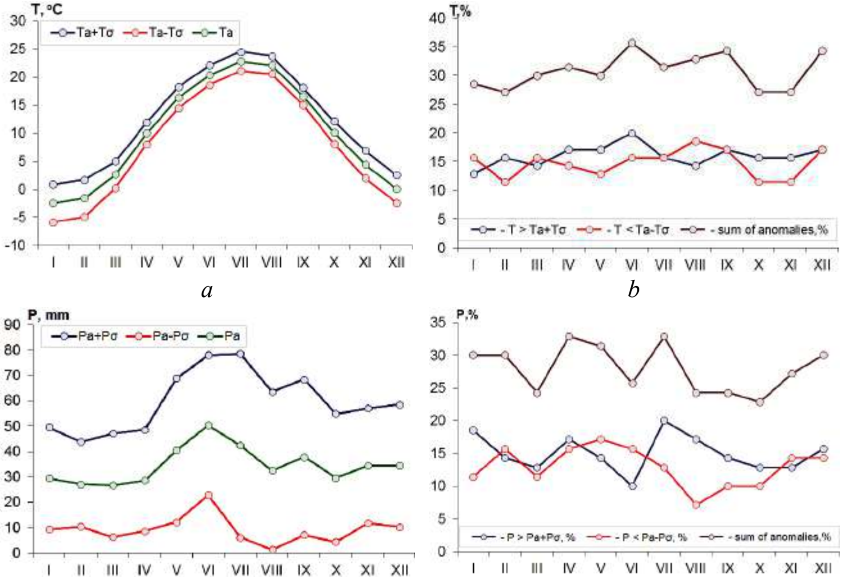
In comparison with the first period (1945–1997), in the second period (1998–2019), there is an increase in the average value of the amount of atmospheric precipitation in almost all months (Fig. 2, *f* (see p. 137)), mainly due to an increase in the minimum possible amount of atmospheric precipitation (Fig. 2, *d* (see p. 137)), 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, see p. 139). 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. 3, *a*, *b*). 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. 3, *c*, *d*), 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, see p. 141) 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:

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

where T_{st}, P_{st} are statistically standardized values of climatic parameters; T_t, P_t – the actual value of the climate parameter at the t-moment of time, year; $\overline{T}, \overline{P}$ – 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



a *b*

c *d*

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

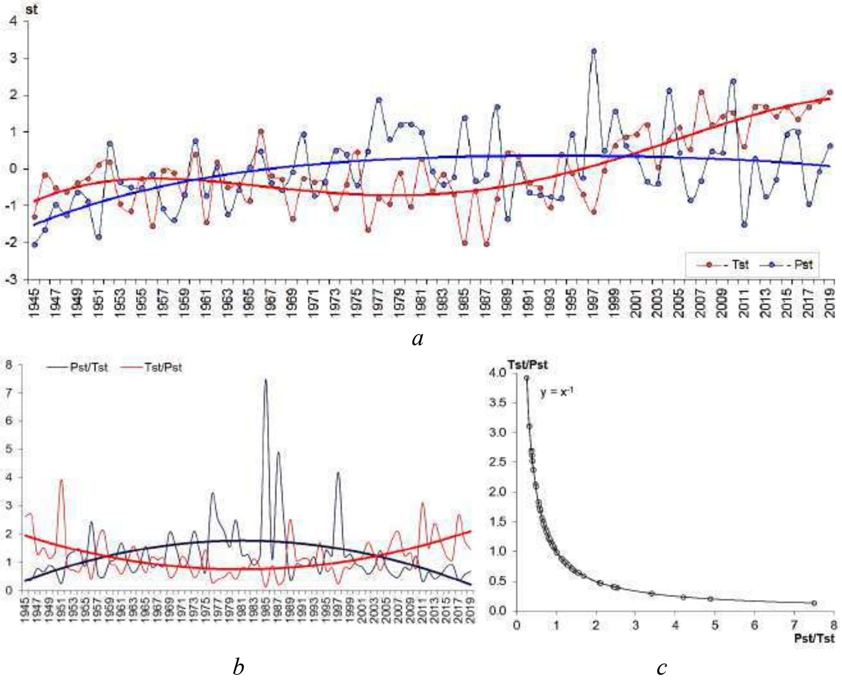
As a result of calculations and the construction of a dynamic graph of statistically standardized values of climatic parameters, three asynchronous periods were determined (Fig. 4, *a* (see p. 141)): I period – 1945–1960, II period – 1961–2000, III period – 2001–2019. As a result of calculating the ratio of values (P_{st} / T_{st}; T_{st} / P_{st}) of climatic parameters (Fig. 4, *b* (see p. 141)), a significant asynchronous influence of air temperature on the amplitude of variational changes in 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. 4, *c* (see p. 141)).

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):

$$\begin{aligned} P_{S(H;W)} &= (1 - p_1) p_1^{t-1}, \\ P_{S(C;D)} &= p_2 (1 - p_2)^{t-1}. \end{aligned} \tag{9}$$

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 0.50p_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 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.



a

b *c*

Figure 4. Asynchronous patterns of changes in climatic parameters in the Steppe zone of Ukraine:

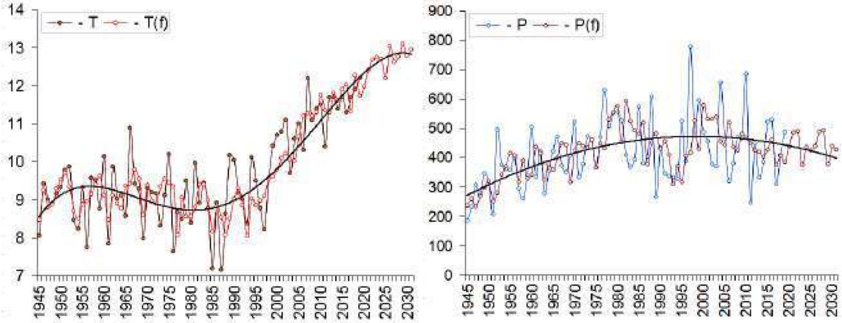
a – dynamics of statistically standardized values of climatic parameters (air temperature (T_{st}, °C) and precipitation (P_{st}, mm); *b* – the dynamics of the ratio of climatic parameter values (P_{st} / T_{st}; T_{st} / P_{st}); *c* – a function of the asynchronous ratio of climatic parameter values

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:

$$\hat{T}_{t+n} = \left(\left(\frac{0.15\mathrm{T}_t}{S_{t-9}} + 0.85(L_{(t-1)} + Tr_{t-1})\right) + \mathrm{n}\left(0.1(L_t - L_{t-1}) + 0.9Tr_{t-1}\right)\right)\times$$
$$\times\left(0.15\frac{\mathrm{T}_t}{L_t} + 0.85S_{t-9}\right)_{t-9+n}, \tag{10}$$

$$\hat{P}_{t+n} = \left(\left(\frac{0.3\mathrm{P}_t}{S_{t-11}} + 0.7(L_{(t-1)} + Tr_{t-1})\right) + \mathrm{n}\left(0.1(L_t - L_{t-1}) + 0.9Tr_{t-1}\right)\right)\times$$
$$\times\left(0.1\frac{\mathrm{P}_t}{L_t} + 0.9S_{t-11}\right)_{t-11+n}, \tag{11}$$

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.



a *b*

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)

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

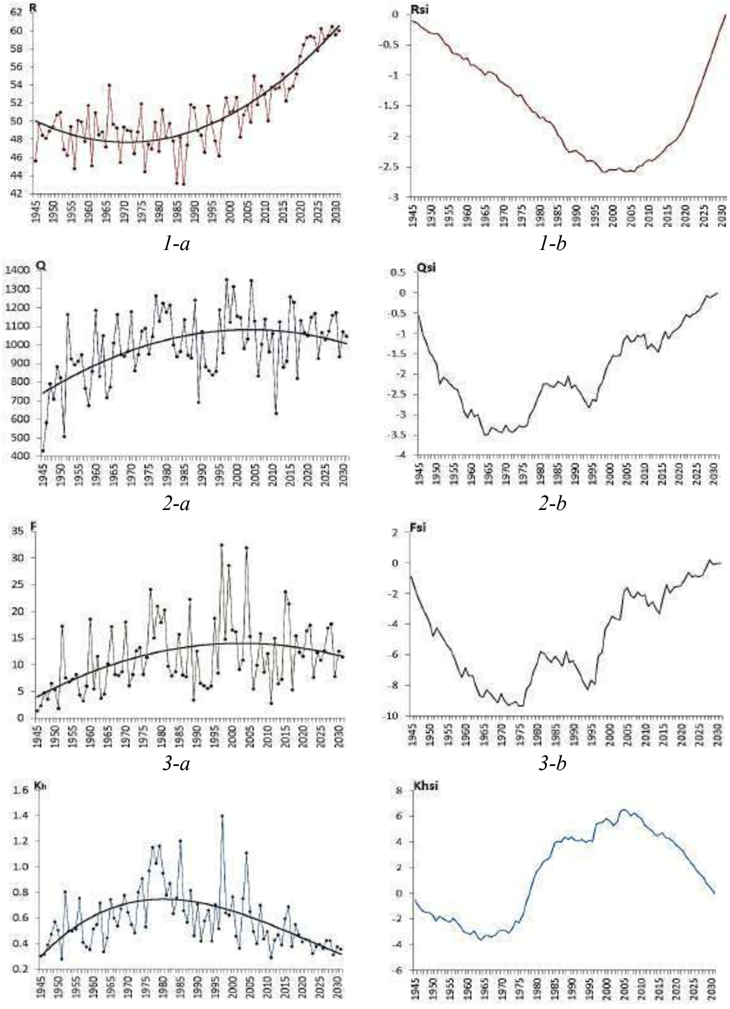
It was determined that if the trend of climate conditions is maintained, with a probability of 93%, there will be a stable trend-cyclic increase in the average annual air temperature by 0.06 °C per year and may reach 12.9 ± 0.2 °C by 2030 (Fig. 5, *a* (see p. 142)), with a probability of 80%, a trend-cyclic 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. 5, *b* (see p. 142)).

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 et al., 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*, *1-b* (see p. 145)) 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 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*, *2-b* (see p. 145)), 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 1,350 to 1,070 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 1,070 to 1,000 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.



1-a *1-b*

2-a *2-b*

3-a *3-b*

4-a *4-b*

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

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*, *3-b* (see p. 145)), 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*, *4-b* (see p. 145)), 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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AGRICULTURAL DEPENDENCE OF THE FORMATION OF WATER BALANCE STABILITY OF THE SLUCH RIVER BASIN UNDER CONDITIONS OF CLIMATE CHANGE

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INTRODUCTION

Climate change is an important global challenge for humanity, which requires an interdisciplinary approach to overcome it. Climate change manifests itself in intensity and frequency of climate anomalies, extreme weather phenomena at different hierarchy levels in space and time. Over the past 30 years there has been a considerable increase in the frequency and intensity of dangerous weather phenomena (Lisetskii et al., 2016; Pichura et al., 2022; Asgarizadeh et al., 2023) causing substantial economic losses (Mei et al., 2020; Koasidis et al., 2023), threatening the existence of basin landscape (Lisetskii et al., 2017; Zhang et al., 2022; Prajapati et al., 2023) and aquatic ecosystems (Pichura et al., 2020a; Lyu et al., 2023), human health and life (Chowdhury et al., 2020; Paquin, 2022; Ma et al., 2022). Therefore, the issue of balanced management of natural resources in developing climate-oriented farming (Coleman et al., 2021; Yin et al., 2023), which requires selection of a special spatial unit of the biosphere, is becoming significant. In this context, the river basin was selected to establish spatio-temporal regularities of organization and correlations of stabilizing (the natural environment) and destabilizing (the anthropogenic environment) components of ecosystems (Pichura et al., 2017; Han et al., 2023; Liu et al., 2023). In particular, the terrain and climatic characteristics of a territory is a determining factor of the formation and functioning of river basins (Zhang et al., 2023; Pei et al., 2023). An excess of the amount of precipitation in comparison with the amount of evaporation and water filtration in soil determines balance of surface runoff from the water catchment area and its accumulation in channel systems (Pichura et al., 2018; Rivaes et al., 2022; Tobias et al., 2023). A river basin is a spatio-temporal water balance stable system, in which precipitation evolves into other elements of water balance that maintains internal, functionally cohesive closed migration currents of surface and internal soil water runoff (Pichura, 2020b; Xie et al., 2023).

The most important function of interrelations of ecosystem components (biotic and abiotic) having genetic, historical and functional relationships, manifesting themselves in continuous exchange of substances, energy and information, is performed at a basin level (Bai et al., 2023; Montes et al., 2023). A river basin acts as an integral system with established ecological, social and economic relationships (Li et al., 2022; Jiang et al., 2023). Moreover, a river basin is a naturally organized territorial unit which allows establishing real spatio-temporal regularities of the consequences and the degree of the impact of human activity on degradation of natural ecosystems (Qu et al., 2020; Lavet et al., 2021; Liu et al., 2023).

Regularities of physical organization of a basin functioning are determined by surface water runoff and discharge of solid substances depending on climatic characteristics and anthropogenic loads on water catchment (Pichura et al., 2020c; Kim et al., 2022). The main anthropogenic factors determining the level of hydro-functioning of a river basin include an industrial complex (Xiong et al., 2021), agriculture and household systems (Prasood et al., 2021; Madeira et al., 2023). Agriculture is a leading large-scale sector in terms of exploitation of natural resources. It causes enormous agrogenic transformation of basin landscape structures (Breus et al., 2021, 2022) and a considerable increase in migration of highly toxic and biogenic substances related to soil erosion, worsening ecological state of water catchment beyond the boundaries of the initial pollution sources (Dudiak et al., 2019a; Santos et al., 2023).

The current problems caused by fresh water scarcity can be exacerbated in the future because of an increasing demand for water resources, their limited availability and lower quality. Scientists predict that the problems of availability of water resources will be deeper that will threaten food security in the world and ecological sustainability of the environment. Agriculture is water-consuming, its share in water footprint reaching 86% (Hoekstra et al., 2008). Agricultural producers worry because of climate changes which worsen due to their activity (Dudiak et al., 2019b). In particular, long-term precipitation deficit in water catchment areas causes meteorological aridity (Wu et al., 2023) which later manifests itself in lower soil moisture content (Breus et al., 2023; Furtak et al., 2023) that is intensified by evaporation (Chen et al., 2019), that disrupts the state of ecological system of a river basin. Therefore, under conditions of climate change and unstable water supply, it is important to maintain balanced functioning of water management and agriculture that will manifest itself in improvement of the system of evaluation and efficient use of available water resources in farming as a component of an integral system in the structure of basin exploitation of natural resources, environmental protection and life maintenance quality on the basis of advanced methods.

Maintenance of balanced water use in the agro-landscapes of the river water catchment area must be based on the ratio of precipitation and the volume of water resources necessary for growing agricultural crops (Pichura et al., 2023a, 2023b), with selection of an optimal structure of crop rotation (Domaratskiy et al., 2018a; Tsai et al., 2023; Benini et al., 2023), substantiation of climate-oriented and resource-saving agro-technological practices (Domaratskiy et al., 2018b, 2019; Korkhova et al., 2023; Skok et al., 2023). Calculation of water footprint (WF) in growing the basic field crops of crop rotation is an efficient instrument for objective evaluation of the volumes of water use and determination of the level of rainwater accumulation in the agro-landscapes of the river water catchment area (Gao et al., 2023; Wen et al., 2023). Water footprint is an instrument which allows for thorough evaluation of a consumer’s or a producer’s attitude toward using fresh water systems (Wu et al., 2022). Calculation of water footprint provides objective information about the use of water volumes for different farming purposes, is a basis for drawing conclusions about sustainability of water resources, their distribution, and also evaluation of ecological, social and economic consequences at a basin level (Pellicer-Martínez et al., 2016; Muratoglu, 2019). Application of the instrument of water footprint allows: establishing distribution of water resources in space and time for industrial, agricultural and household needs; evaluating sustainability and efficiency of using water resources within the water catchment area; substantiating strategic directions in the development of water sector and agriculture at different levels of basin management (Novoa et al., 2019; D'Ambrosio et al., 2020; Sauvé et al., 2021; Song et al., 2023).

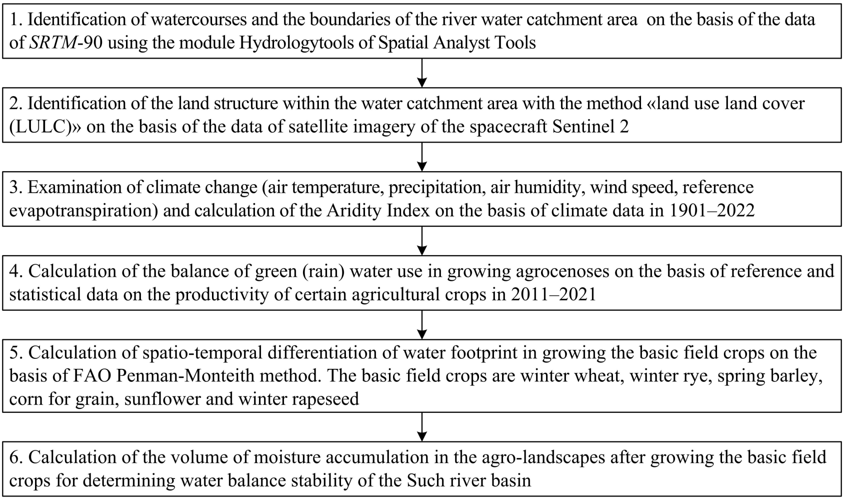
The purpose of the research is to calculate water footprint in growing the basic field crops and determine additional water accumulation for maintaining the hydro-functioning of the Sluch river basin under conditions of climate change.

MATERIAL AND METHODS

Research scheme and materials

The scheme of the research of the water catchment area of the Sluch river and calculation of water footprint in growing agricultural crops involves six logically successive blocks of research organization (Fig. 1, see p. 156).

In order to identify watercourses, establish their orders and determine the boundaries of the water catchment area of the Sluch river basin, we used a digital model of the terrain (DMT) on the basis of the data of *SRTM*-90 with spatial resolution of 90 × 60 m/pixel, which was displayed on the official website of the USA Geological Survey (https://earthexplorer.usgs.gov/). The research was carried out by means of the program *ArcGIS* on the basis of the DMT using an improved algorithm (Pichura et al., 2017, 2020b) of the hydrological geo-modeling of the module Hydrologytools of Spatial Analyst Tools. In order to divide the river basin into groups depending on the order of the main stream, we applied the approach of Strahler-Filosofov (Strahler, 1952).



1. Identification of watercourses and the boundaries of the river water catchment area on the basis of the data of *SRTM*-90 using the module Hydrologytools of Spatial Analyst Tools

2. Identification of the land structure within the water catchment area with the method «land use land cover (LULC)» on the basis of the data of satellite imagery of the spacecraft Sentinel 2

3. Examination of climate change (air temperature, precipitation, air humidity, wind speed, reference evapotranspiration) and calculation of the Aridity Index on the basis of climate data in 1901–2022

4. Calculation of the balance of green (rain) water use in growing agrocenoses on the basis of reference and statistical data on the productivity of certain agricultural crops in 2011–2021

5. Calculation of spatio-temporal differentiation of water footprint in growing the basic field crops on the basis of FAO Penman-Monteith method. The basic field crops are winter wheat, winter rye, spring barley, corn for grain, sunflower and winter rapeseed

6. Calculation of the volume of moisture accumulation in the agro-landscapes after growing the basic field crops for determining water balance stability of the Such river basin

Figure 1. Structural-logical methodological scheme of the research of the water catchment area of the Sluch river and calculation of water footprint in growing agricultural crops

The land structure of the Sluch basin was calculated on the basis of the data of the satellite imagery of the spacecraft Sentinel 2 (with spatial resolution of 10 m/pixel) created on October 15–16, 2022 using the method “land use land cover (LULC)” of *ArcGIS*. Spatio-temporal regularities of changes in climatic conditions in the water catchment area of the river basin between 1901 and 2022 were established on the basis of the data of Climatic Research Unit of the University of East Anglia (https://crudata.uea.ac.uk/cru/data/hrg/) and the data of NASA POWER (https://power.larc.nasa.gov/data-access-viewer/). To calculate evapotranspiration processes, we used the reference data of FAO (https://www.fao.org/3/X0490E/x0490e00.htm#Contents).

The coefficients of water use by the basic field crops under different conditions of natural moisture were taken from the reference books for typical physical-geographical conditions of Polissia in Ukraine (http://agro-business.com.ua/ahrarni-kultury/item/16506-systema-povnoho-zabezpechennia-posiviv-volohoiu-za-umov-zroshennia.html), which correspond to the conditions of growing agrocenoses within the Sluch river basin.

Characteristic of the research territory

The Sluch river begins its flow in a small lake feeding on groundwater, located in a gulch and 1 km eastward from the village Chervona Sluch in Khmelnytskyi region in Ukraine, at elevation of 320 m (Fig. 2, *a* (see p. 158)). The Sluch river empties from the right tributary to the river Horyn within the village Liutynsk in Rivne region. The total length of the river equals 451 m, the water catchment area is 13.83 thous. km^2, the fall of the stream is 183 m (Fig. 2, *b* (see p. 158)).

The terrain height within the river basin from its source to the estuary ranges from 376 m to 137 m (Fig. 2, *c* (see p. 158)), the average slope of the water surface is smooth, being 0.4%. The upper part of the basin is an elevated plain, split by incised river valleys 50–100 m long and a dense gulch network. The average density of the river network is 0.39 km/km^2, the density of the river network reaches 0.7 km/km^2 in the upper part of the Sluch basin. The basin morphometry has a form elongated northward, 300 km long, with the medium and maximum width – 46 km and 110 km, respectively. The river catchment area is located in two geomorphological zones, namely: the upper and the middle parts of the basin are in Volyn-Podillia Upland and its branches, called Volyn Polissia; the lower part of the water catchment area is within the great plain Polissia (Pripyat Polissia). The river stream is meandering, it has steep banks from 20–40 m to 50 m high in some places, the banks are moderately steep, rarely – sloping 5–15 m high in other places. The plain is 1.5–5.0 km wide in the lower course. The floodplain is double sided, overgrown with grassland vegetation, waterlogged in some places. The woodiness of the basin is 30.8%, other vegetation (meadows, windbreaks, vegetation on gulch lands) – 10.7%, waterlogging – 13.0%, water bodies – 0.3%, farmlands – 39.7%, settlements – 5.4% (Fig. 2, *d*).

On the Sluch river, in the city Novohrad-Volynskyi, there is a water storage reservoir with the water volume of 1.8 mln m^3 (the area is 95.5 ha), which is used for farming and households. Water consumption is 1.96 mln m^3 per year (Priymachenko, 2013). The Sluch river is used as a source of hydro-energy (Myropilksa HES, Liubarska HES, Pedynkivska HES). The ponds within the Sluch basin are designed for fisheries. Flow distribution throughout the year is not even.

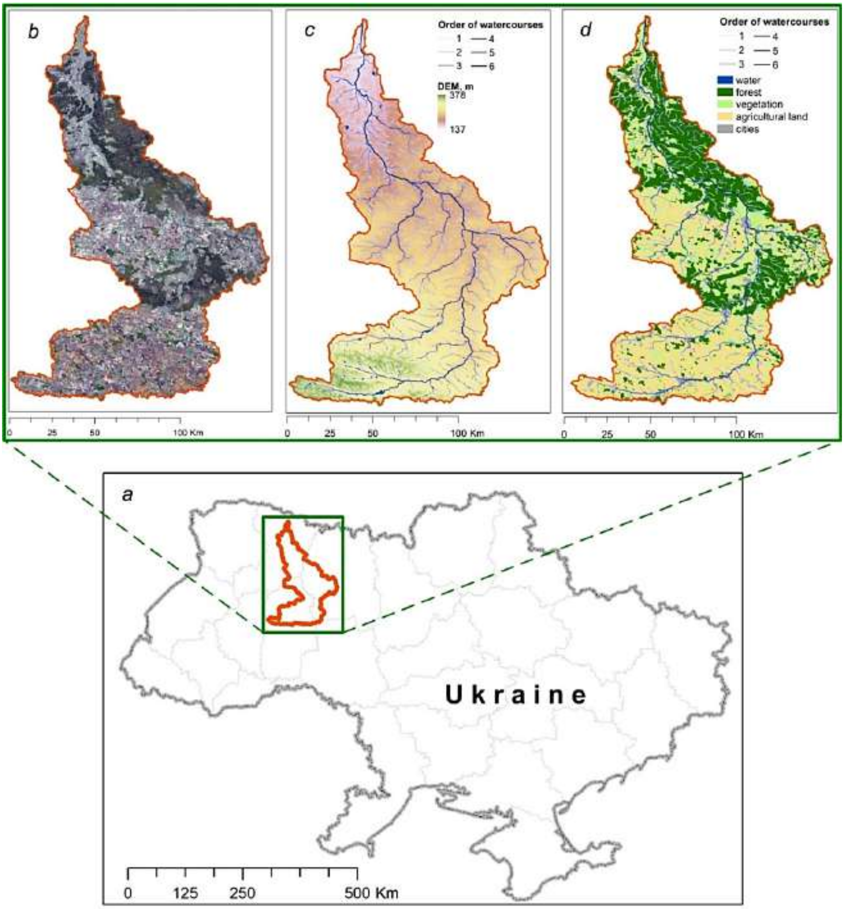


Figure 2. Spatial location and characteristic of the Sluch river basin:
a – location in the territory of Ukraine; *b* – satellite imagery of the spacecraft Sentinel 2 created on October 15–16, 2022; *c* – a digital model of the terrain and distribution of the hydrological network within the basin; *d* – the structure of farmlands

It depends on the amount of precipitation and the air temperature regime. Most of the flow is observed over the period of spring flooding, within 40–80% of the river runoff. In a summer low-water period the river mainly feeds on groundwater (Biedunkova, 2013). Floods occur in a summer-autumn period. The largest water storage in snow equals 102 mm, the medium – 47 mm, supplied by 10% – 86 mm, by 25% – 65 mm. The amount of annual precipitation for 50% of the years of the research is 562 mm, for 75% – 481 mm, for 95% – 401 mm. The river velocity under maximum water losses reaches 1.0–1.4 m/c, the average velocity is 0.3–0.5 m/s in a low-water period. On average, mineralization of surface water is: in spring floods – 313 mg/dm³; a spring-summer low-water period – 321 mg/dm³; a winter low-water period – 349 mg/dm³. According to the complex ecological evaluation in the period of 2005–2021, the quality of surface water in the Sluch river in most cases of sample collection was considered to be of Class II – "good" condition, with excessive content of nitrite nitrogen, the index of BOD_5 (biochemical oxygen demand over five days) and phosphate phosphorus (Biedunkova et al., 2023), that is an evidence of the presence of biogenic elements of anthropogenic origin in the water composition of the investigated river.

The method for calculating Aridity Index (AI).

The AI is an aridity index which is determined on the basis of the ratio of annual precipitation (P) to annual values of reference evapotranspiration (ET_o) by the formula (Stadler, 2005; Colantoni et al., 2015):

$$AI = P / ET_o . \tag{1}$$

The aridity index (*AI*) can be defined as a bioclimatic index, since it involves physical phenomena (precipitation and evaporation), and biological processes (plant transpiration). In addition, this index is one of the most important indexes for investigating processes of desertification (Sgroi et al., 2014). As a rule, the value of the AI lower than 0.5 indicates arid or semi-arid territories, whereas the value over 0.65 indicates humid or hyper-humid zones as given in Table 1 (see p. 160).

Table 1. Aridity index values

Climate classification	**Aridity Index (*AI*) values**
Hyper-arid	≤0.05
Arid	0.05–0.20
Semi-arid	0.20–0.50
Dry sub-humid	0.50–0.65
Humid	0.65–0.75
Hyper-humid	>0.75

The Aridity Index is used in the United Nations Environment Programme (http://www.unep.org/), Food and Agriculture Organization (http://www.fao.org/) and United Nations Convention to Combat Desertification (http://www.unccd.int/main.php) for classifying climates, evaluating the supply of precipitation and irrigation management in a certain research territory.

Method for calculating crop evapotranspiration (ET_c)

Spatio-temporal differentiation of evapotranspiration of green and blue water in the period of growing the basic field agricultural crops was calculated on the basis of FAO Penman-Monteith method, which is based on calculation of reference evapotranspiration (ET_o) and further computation of crop evapotranspiration (ET_c) involving the crop coefficient (K_c).

The FAO Penman-Monteith method is maintained as the sole standard method for the computation of ET_o from meteorological data:

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T + 273} u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}, \qquad (2)$$

where ET_o – reference evapotranspiration, mm/day; R_n – net radiation at the crop surface, MJ/m^2 day^1; G – soil heat flux density, MJ/m^2 day^1; T – air temperature at 2 m height, °C; u_2 – wind speed at 2 m height, m/s; e_s – saturation vapour pressure, kPa; e_a – actual vapour pressure, kPa; e_s–e_a – saturation vapour pressure deficit, kPa; Δ – slope vapour pressure curve, kPa/°C; γ – psychrometric constant, kPa/°C.

The index ET_o is calculated on the basis of climatic parameters. It reflects evaporation in a certain region in a particular period of the year, but it does not cover yield specificity and soil characteristics. Crop evapotranspiration (ET_c) differs from reference evapotranspiration (ET_o), since it involves aerodynamic features of yield stability of agricultural crops (K_c). The K_c value changes depending on certain crop characteristics and only partially depends on climate.

The index of crop evapotranspiration (ET_c) is calculated by the formula:

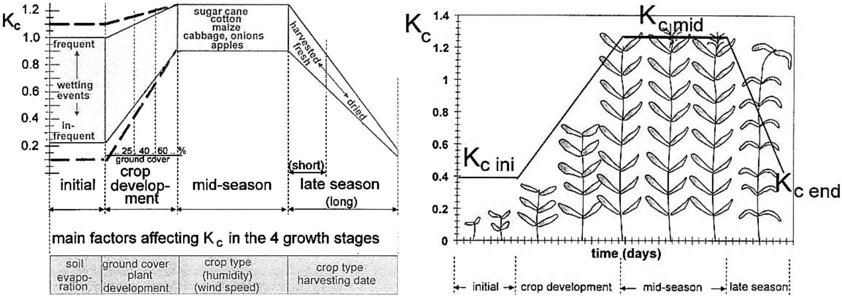
$$ET_c = ET_0 \times K_c\,. \tag{3}$$

The value of *crop evapotranspiration* ET_c is calculated on the condition that the following factors are excluded: crop growth rate, groundwater and salinity, sowing density, presence of pests and diseases, weediness and soil fertility. The K_c coefficient involves the values of transpiration characteristics of a certain crop and average effects of evaporation from soil.

Calculation of ET_c includes four stages, namely:

1. Identifying growth stages of certain crops. Soil cover, plant height and leaf area change over the course of plant growth. Due to the differences in evaporation at different growth stages, the K_c values for a certain crop change over the entire vegetation period, which, according to the method of FAO Penman-Monteith, is divided into four phenological growth stages (Fig. 3, *a* (see p. 162)): L_{ini} – initial, L_{dev} – crop development, L_{mid} – mid-season, L_{late} – late season. Each crop has its own duration of a certain vegetation stage in accordance with sowing dates and the region of cultivation. Typical dates of individual phenological stages of plant growth are given in the sources of FAO (https://www.fao.org/3/X0490E/x0490e0b.htm#TopOfPage). In particular, three values are necessary for describing and creating a curve of yield coefficients (Fig. 3, *b*, K_c (see p. 162)): at the initial stage (K_{c_ini}), in the mid-season (K_{c_mid}), and in the late season (K_{c_and}).

Table 2 (see p. 162), according to FAO grading, presents typical values of yield coefficients for different agricultural crops, which have the largest portion in crop rotation in the research region. The coefficients belonging to one group of crops are usually similar, since plant height, leaf area, soil cover and management of water resources are almost identical.



a *b*

Figure 3. Major phenological stages of plant growth for calculating K_c: *a* – typical ranges expected in K_c for the four growth stages; *b* – generalized crop coefficient curve for the single crop coefficient approach

Table 2. Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non-stressed, well-managed crops in subhumid climates ($RH_{min} \approx 45\%$, $u_2 \approx 2$ m/s) for use with the FAO Penman-Monteith ET_o

Crop	Maximum Crop Height (h), m	K_{c_ini}	K_{c_mid}	K_{c_and}
Winter wheat	1.0	0.40	1.15	0.25
Winter rye	1.0	0.40	1.15	0.25
Spring wheat	1.0	0.30	1.15	0.25
Spring barley	1.0	0.30	1.15	0.25
Corn for grain	2.0	0.30	1.20	0.35
Sunflower	2.0	0.35	1.00	0.35
Winter rapeseed	0.6	0.35	1.00	0.35

2. Adjusting the selected K_c coefficients for frequency of wetting or climatic conditions throughout the vegetation period. The K_c values at the initial stage and the stage of crop development depend on the impact of a fluctuation-induced force of the frequency of wetting the crop area, therefore the values of the K_{c_ini} coefficient

should be specified. The K_{c_mid} and K_{c_and} values are adjusted according to weather conditions of the research territory using the actual data of the average value of wind speed (u_2, m/s) and relative air humidity ($RH_{\min}$, %) in the territory of growing certain agricultural crops.

Adjustment of coefficients is made by the formula:

$$K_{c\_(mid\ or\ end)} = K_{c\_(mid\ or\ end)(Tab)} + \left[0.04\left(u_2 - 2\right) - 0.004\left(RH_{min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3}, \quad (4)$$

where $K_{c\_(mid\ or\ end)\ (Tab)}$ – value for K_{c_mid} and K_{c_end} taken from Table 1; u_2 – mean value for daily wind speed at 2 m height over grass during the mid and late seasons growth stage (m/s), for $1\ \text{m/s} \le u_2 \le 6\ \text{m/s}$; $RH_{\min}$ – mean value for daily minimum relative humidity during the mid and late seasons growth stage (%), for $20\% \le RH_{\min} \le 80\%$; h – mean plant height during the mid and late seasons stage (m) for $0.1\ \text{m} < h < 10\ \text{m}$.

For late seasons stage no adjustment is made when $K_{c\_end\ (Tab)} < 0.45$ (i.e., $K_{c\_end} = K_{c\_end\ (Tab)}$).

Where no data on u_2 or $RH_{\min}$ are available, the general classification for wind speed and humidity data given in Table 3 can be used.

Table 3. Empirical estimates of monthly wind speed data (u_2) and typical values for $RH_{\min}$ compared with RH_{mean} for general climatic classifications

Description	u_2, m/s	Climatic classification	$RH_{\min}$, %	RH_{mean}, %
Light wind	≤1.0	Arid	20	45
Light to moderate wind	2.0	Semi-arid	30	55
Moderate to strong wind	4.0	Sub-humid	45	70
Strong wind	≥5.0	Humid	70	85
General global conditions	2.0	Very humid	80	90

3. Creation of the curve of yield coefficients allows determining the K_c value for any vegetation period. Only three point values for K_c are required to describe and to construct the K_c curve. Divide the growing period into four general growth

stages that describe crop phenology or development (initial, crop development, mid-season, and late season stage), determine the lengths of the growth stages, and identify the three K_c values that correspond to K_{c_ini}, K_{c_mid} and K_{c_end}.

4. Calculation of ET_c by formula 3. After finding the K_c values, crop evapotranspiration (ET_c) is calculated, through multiplying the K_c value by the corresponding ET_o values.

The K_c coefficient for any period of the growing season can be derived by considering that during the initial and mid-season stages K_c is constant and equal to the K_c value of the growth stage under consideration. During the crop development and late season stage, K_c varies linearly between the K_c at the end of the previous stage (K_{c_prev}) and the K_c at the beginning of the next stage (K_{c_next}), which is K_{c_end} in the case of the late season stage:

$$K_{ci} = K_{cprev} + \left[\frac{i - \Sigma\left(L_{prev}\right)}{L_{stage}}\right]\left(K_{cnext} - K_{cprev}\right), \tag{5}$$

where i – day number within the growing season [1… length of the growing season]; K_{ci} – crop coefficient on day i; L_{stage} – length of the stage under consideration, days; $\Sigma(L_{prev})$ – sum of the lengths of all previous stages, days.

Space imagery processing, cartogram creation, spatio-temporal, correlation and regression analyses were performed using the licensed program product ArcGis 10.6 and Microsoft Excel 2010.

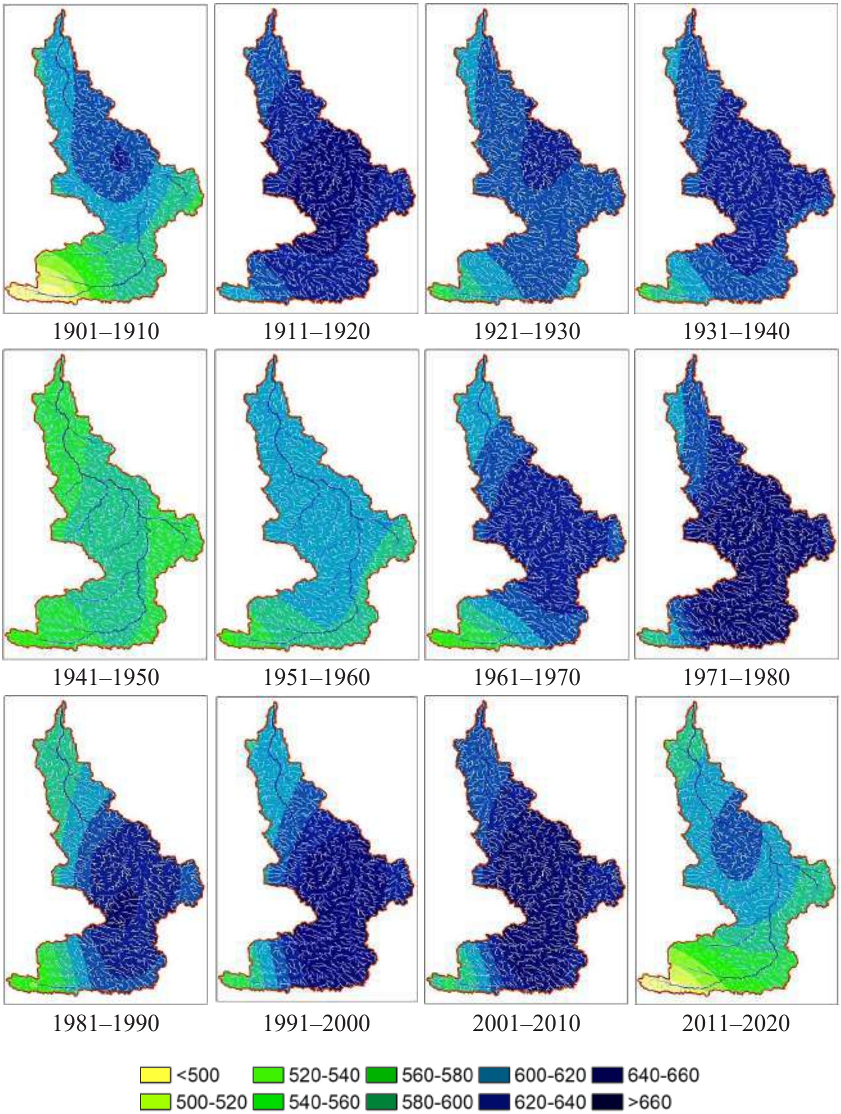
RESULTS AND DISCUSSION

Research of climate change

The speed of the development of plant cover and the time of reaching effective entire cover depend on weather conditions on the whole, and precipitation and the air temperature in particular. Therefore, the period between sowing and effective entire cover of agrocenoses, the level of water use, the duration of certain phenological stages and productivity, change depending on climate, physical-geographical conditions of the area (latitude, longitude), sowing dates, varietal characteristics and the level of agro-technological practices. After reaching effective entire plant cover, the speed of phenological development (flowering, seed or grain development, maturation and dieback) depends on a plant genotype and agrocenosis plasticity with regard to climatic conditions. A lack of precipitation and high temperatures reduce the duration of phenological stages, accelerate plant maturation and dieback. In particular, long-term air temperature (>35 °C) and moisture deficit accelerate the rate of maturation, reduce the duration of mid- and late-season stages of plant vegetation that causes an increase in the level of the values of evapotranspiration processes, a fall in agrocenosis productivity and soil moisture deficit. Therefore, complex evaluation of moisture conditions of any territory, forecasting productivity, calculation of water use and moisture supply for agricultural crops are performed taking into consideration agro-meteorological indexes, in particular: precipitation, air temperature, wind speed, and also derivative indicators (climate energy, air humidity, evapotranspiration, climate coefficients and idexes etc.).

The water catchment area of the Sluch river basin belongs to the zone of an optimal level of moisture supply and good conditions for obtaining high yields of agricultural crops. Over the past 120 years (Fig. 4, see p. 166) the annual amount of precipitation within the water catchment area ranged from 487 mm to 716 mm. A relatively low value of precipitation is registered in the river source area (487–586 mm), in the middle part of the main course the value ranges from 580 mm to 716 mm, in the river mouth it is between 590 mm and 630 mm. Over the observation period, there were four ten-year periods with the maximum value of precipitation and three periods with the minimum value of atmospheric moisture supply (Fig. 7, *a* (see p. 171)).

Air temperature is a factor of the formation of water content of hydrological network, soil moisture reserves, water footprint in growing agricultural crops, the duration of phenological stages of plants and activeness of evapotranspiration process. Since the 80s of the 20th century (Fig. 7, *b* (see p. 171)), there has been a gradual increase in the air temperature regime in the territory of the Such



1901–1910 1911–1920 1921–1930 1931–1940

1941–1950 1951–1960 1961–1970 1971–1980

1981–1990 1991–2000 2001–2010 2011–2020

Figure 4. Spatio-temporal differentiation of the amount of atmospheric precipitation within the Sluch river basin in 1901–2020

river basin. Over the past 40 years the average annual temperature in the water catchment area has risen by 1.9 °C on average, that caused a considerable increase in evapotranspiration processes, a fall in moisture supply in the basin landscape and aquatic territorial structures. It also determined a rise in the agrocenosis water use for the formation of a unit of production (t/ha).

Over the past 120 years the value of reference evapotranspiration (ET_o) in the water catchment area of the Sluch river has ranged between 1.72 and 2.25 mm/day (Fig. 5, see p. 168). Its minimal value was registered in the period of wet years: in 1921–1930 – 1.79–1.94 mm/day and in 1971–1980 – 1.72–1.88 mm/day (Fig. 7, *c* (see p. 171)). The maximum ET_o value has been registered over the past 30 years, ranging between 1.86 and 2.25 mm/day, that is determined by an increase in the air temperature and asynchronous precipitation. High values of reference evapotranspiration were observed within the basin landscape and aquatic territorial structures of the upper course of the Sluch river – from 1.87 mm/day (the wet year) to 2.25 mm/day (the dry year). Within the basin of the river middle course, the ET_o value ranged from 1.80 to 2.15 mm/day, from 1.72 mm/day to 2.00 mm/day in the river mouth.

Spatio-temporal variation of ET_o is an important indicator of aridity, changes in the formation of water regime, moisture supply in basin landscape structures, the level of plant water use, the volume of water footprint in growing agrocenosis, etc. In particular, aridity is a stochastic climatic phenomenon that occurs as a consequence of substantial deficit of precipitation and an extreme increase in the air temperature, which have a negative impact on the functioning of basin landscape and aquatic territorial structures, and a reduction in agrocenosis productivity. Aridity is a part of a natural climatic cycle that can last several months or years. It is a complex phenomenon, the frequency of its manifestations has increased considerably over the past years causing negative ecological and socio-economic consequences for regions with its manifestations. Aridity is a result of a combination of natural and anthropogenic

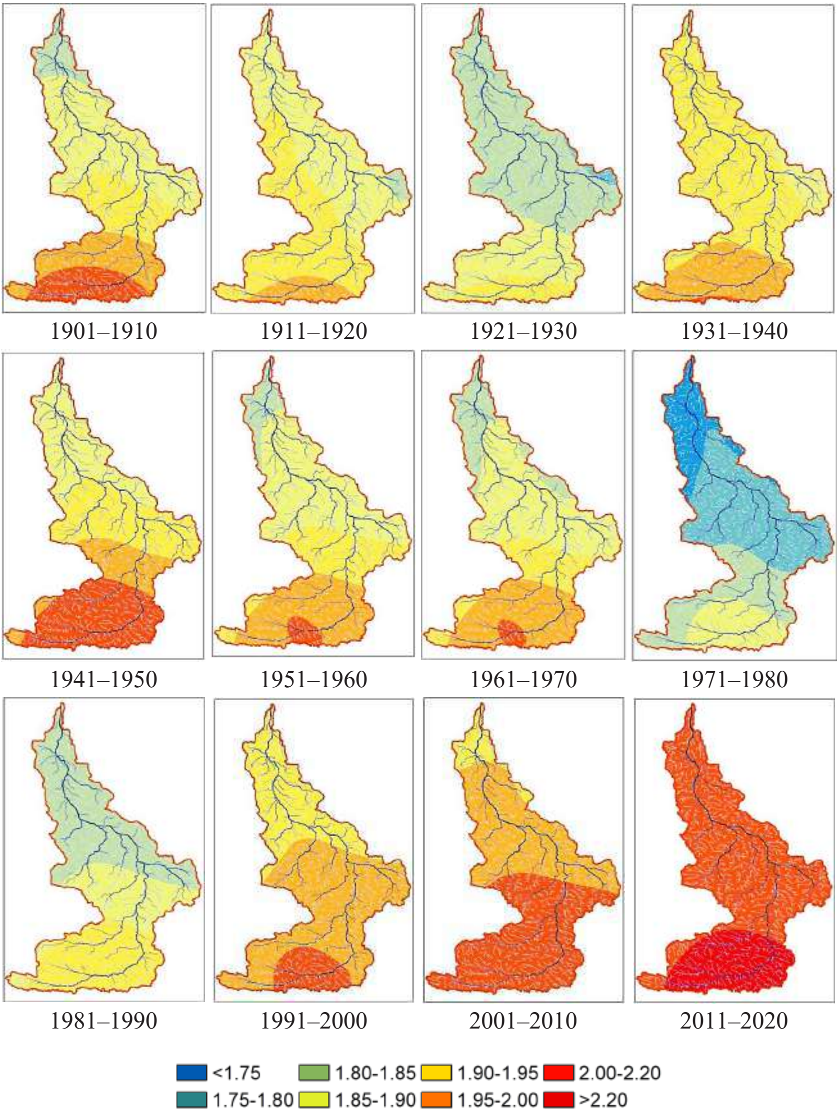

1901–1910 1911–1920 1921–1930 1931–1940
1941–1950 1951–1960 1961–1970 1971–1980
1981–1990 1991–2000 2001–2010 2011–2020

Figure 5. Spatio-temporal differentiation of the reference evapotranspiration value (ET_o, mm/day) within the Sluch river basin in 1901–2020

factors that causes water deficit, deterioration of the circulation of substances in natural ecosystems and functioning of the socio-economic sector. Therefore, determination of the periods and characteristics of aridity allows establishing its degree, cyclicity and tendencies, identifying risks of its manifestations, that makes it possible to outline a number of measures aimed at preventing climate changes, that will be realized through implementation of climate-adaptive technologies in different areas of economy. In climatology, different types of aridity are identified by means of the Aridity Index which characterizes the degree of aridity on the basis of one or several climate indicators. The ratio of the amount of precipitation and reference evapotranspiration is used for it. Aridity Indexes reflect spatio-temporal regularities and conditions of climate change, manifestations of dry climate anomalies, delays of hydrological impacts (moisture losses from soil and water from aquatic areas). The degree of aridity affects agrocenosis productivity (t/ha) and an increase in the coefficient of water use (m^3/t), that characterize spatio-temporal changes in water footprint in growing agricultural crops.

Calculation of the Aridity Index allows establishing spatio-temporal regularities of climate change, classifying them, determining the periods or years with probable manifestations of aridity, identifying the trend of complex evaluation of the changes in moisture supply of the river water catchment area and agro-meteorological characteristics of agricultural crop yields. According to the results of spatio-temporal calculation of the *AI* over the past 40 years in the water catchment area of the Sluch river basin, there has been considerable warming and a reduction in moisture supply (Fig. 6 (see p. 170), Fig. 7, *d* (see p. 171)).

Over 120 years of observations the *AI* value has ranged from 0.61 to 1.08. The climate within the river basin was considered to be “hyper-humid” in most of the years. However, climate changes over the past 10–15 years have caused considerable spatial differentiation of moisture supply in the water catchment area of the Sluch river, in particular: 33.5% of the water catchment area which is located within the upper river course is characterized

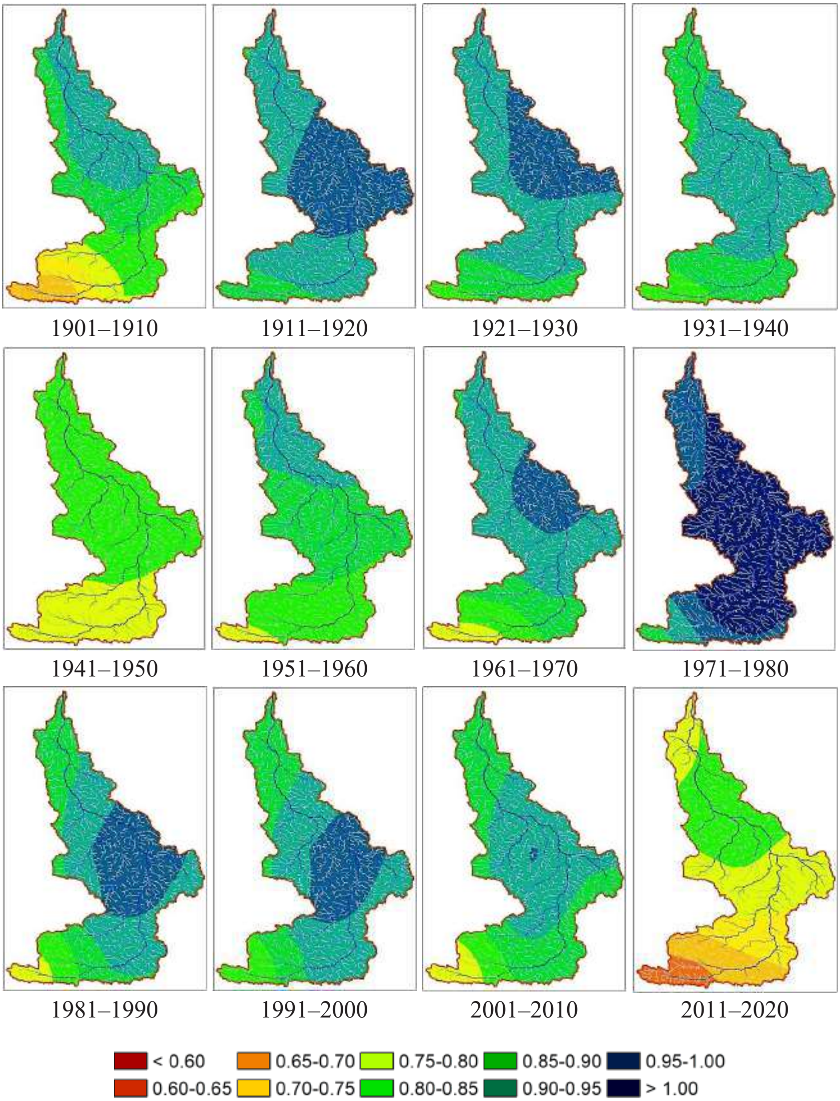
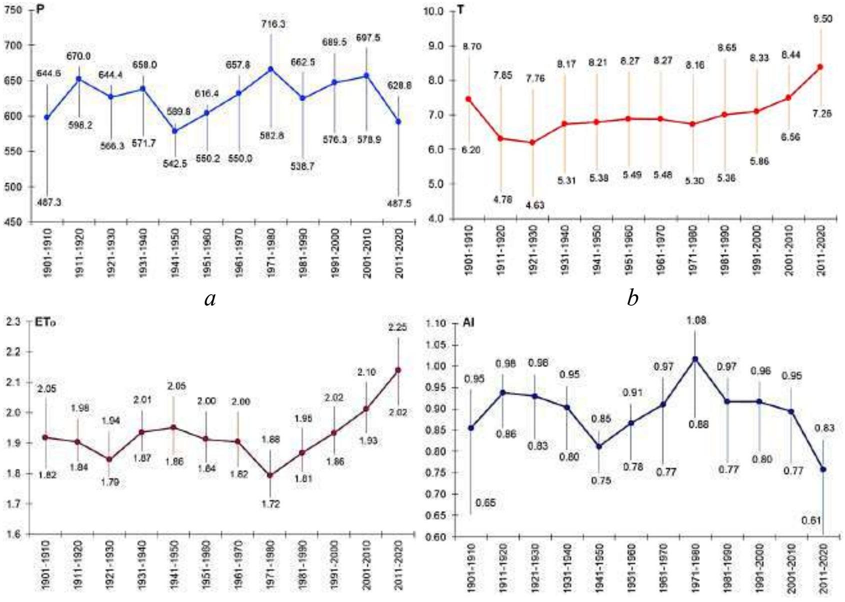


Figure 6. Spatio-temporal differentiation of the Aridity Index (*AT*) value within the Sluch river basin in 1901–2020

by dry sub-humid (6.5%) and humid climate (27.0%). Though currently the Sluch river basin is still a natural region with good moisture supply, but the tendencies of global warming show inevitability of an increase in the water catchment area with a dry sub-humid climate in the upper part of the river basin that will result in a reduction in water content and may cause small streams' drying up in the upper course of the Sluch river. In particular, climate-related problems of the upper part of the water catchment area are being exacerbated by a high level of anthropogenically damaged lands (farmlands and populated areas) at the level of 68.9% and limited natural landscapes (lands covered by forests and other natural vegetation, wetlands) – 31.1%. It is worth noting that natural



a *b*

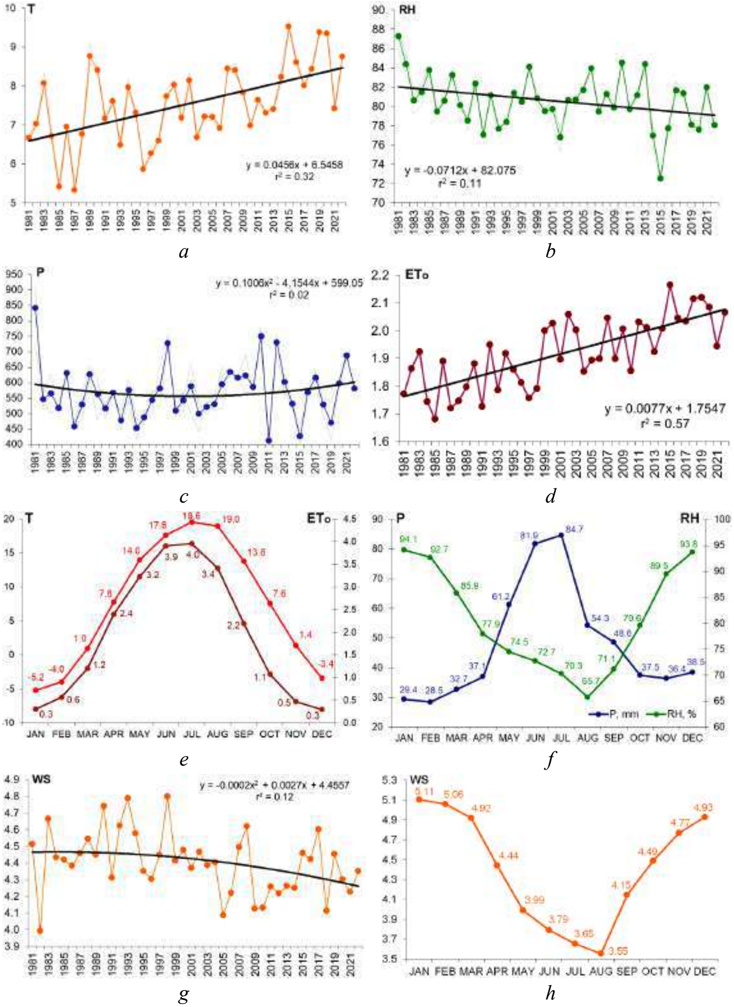
c *d*

Figure 7. Climatic characteristics of the water catchment area of the Sluch river in 1901–2020:

a – amount of precipitation per year (*P*), mm; *b* – average annual air temperature (*T*), °C; *c* – reference evapotranspiration (ET_o, mm/day); *d* – aridity index (*AI*) value vegetation performs stabilizing and climate-regulating function for the environment, contributes to a reduction in evapotranspiration processes and aridity manifestations. According to the ratio “anthropogenically damaged lands and natural lands”, the upper part of the water catchment area is characterized by a “destructive” type of the state of the basin landscape structures.

The past 40 years are characterized by the formation of new climatic conditions with a distinctive increase in the temperature regime and asynchronous changes in precipitation, which cause moisture deficit, a fall in the level of circulation of substances in the ecosystem of the Sluch river basin, application of climate-resilient plant breeding and use of water-saving agricultural technologies in order to obtain stable yields and retain soil moisture. Climatic conditions of a certain year form the volume of water footprint that is defined as the amount of green water which evaporates and green water which is used by plants throughout their life cycle. The level of plant use and evaporation of green water depends on the amount of precipitation, a change in the air temperature and wind speed throughout the vegetation period of agrocenosis. Therefore, the research on the dynamics of green water use on non-irrigated lands under the basic field crops was conducted for the years with different levels of moisture supply within the Sluch river basin in 1981–2022. This period of observations is characterized by an increase of the average annual air temperature from 6.6 °C to 8.5 °C (Fig. 8, *a* (see p. 173)) and unstable precipitation with a rise in the variance from 11% to 16% (Fig. 8, *c* (see p. 173)), that led to a reduction in the average annual value of air humidity from 86% to 79% (Fig. 8, *b* (see p. 173)) and an increase in reference evapotranspiration by 0.3 mm/day (Fig. 8, *d* (see p. 173)).

The results of correlation analysis of the impact of the basic climate indexes on the change in the value of reference evapotranspiration (ET_o) allowed establishing that the main climatic component of differentiation of ET_o is air temperature. The level of correlation between the average annual values of T and ET_o equals 0.79, that of the annual monthly values being 0.95. The regularity of a change in RH and ET_o was also found,



a *b*

c *d*

e *f*

g *h*

Figure 8. Climatic characteristics of the water catchment area of the Sluch river in 1981–2022:

a – average annual air temperature (*T*), °C; *b* – average annual air humidity (*RH*), %; *c* – amount of precipitation per year (*P*), mm; *d* – reference evapotranspiration (ET_o), mm/day; *e* – average monthly *T* and ET_o values; *f* – average monthly *P* and *RH* values; *g* – average annual wind speed (*WS*), m/s; *h* – average monthly *WS* value the correlation being 0.35 for the average annual values and 0.91 for the average monthly values.

Calculation of the average annual ET_o value on the basis of meteorological data:

$$ET_o = \begin{cases} 0.1462T + 0.8324; & r = 0.95,\ r^2 = 0.90 \\ -0.1289RH + 12.318; & r = 0.91,\ r^2 = 0.83 \\ 0.02306P + 0.10557T + 0.03783; & r = 0.96,\ r^2 = 0.92 \\ -0.00774RH - 2.27485WS + 12.5608; & r = 0.95,\ r^2 = 0.90 \end{cases}. \qquad (6)$$

Calculation of the average monthly ET_o value on the basis of meteorological data:

$$ET_o = \begin{cases} 0.1462T + 0.8324; & r = 0.95,\ r^2 = 0.90 \\ -0.1289RH + 12.318; & r = 0.91,\ r^2 = 0.83 \\ 0.02306P + 0.10557T + 0.03783; & r = 0.96,\ r^2 = 0.92 \\ -0.00774RH - 2.27485WS + 12.5608; & r = 0.95,\ r^2 = 0.90 \end{cases}. \qquad (7)$$

According to the method FAO, crop evapotranspiration (ET_c) was specified in calculation of the values of reference evapotranspiration (ET_o), further calculation of green water use by certain crop species throughout the life cycle was performed and the importance of the indicator of wind speed (WS; u_2) and relative air humidity (RH) was established. A high level of correlation of the two-factor model of calculation of ET_o depending on RH and WS, aimed at calculating the average annual ET_o values was established for the water catchment area of the Sluch river. The level of the model approximation is 0.44, the average monthly value (ET_o) being 0.90. The proposed models are optimal for calculation of spatio-temporal differentiation of ET_o within the water catchment area of the Sluch river on the basis of different climate data.

Seasonal characteristics of climate changes (Fig. 8, *e*, *f*, *h* (see p. 173)) are necessary for determining the coefficient of productivity (K_c), calculating crop evapotranspiration (ET_c) and water footprint (WF, m^3/year) in growing the basic agricultural crops within the Sluch river basin.

The balance of green (rain) water use in growing agrocenosis on the basis of reference and statistical data on productivity of certain agricultural crops

In 2020 the portion of farmlands in the land structure of Ukraine was 68.7% (41.4 mln ha), including: arable lands – 79.0% (32.7 mln ha), pastures – 12.8% (5.3 mln ha), hayfields – 5.56% (2.3 mln ha), perennial plantations – 2.17% (0.9 mln ha), fallow lands – 0.47% (0.2 mln ha). In the structure of farmlands 53.4% of crop areas are under grain and leguminous crops, including: wheat – 23.8%, barley – 9.0%, corn for grain – 16.6%. 33.5% of crop areas are under industrial crops: sunflower – 22.4% and rapeseed – 3.6%. 13.1% of crop areas are under other crops.

Water use by agricultural crops depends on plant biological characteristics, productivity, soil-climate and organizational-technological conditions. The coefficient of water use mainly depends on soil-climate conditions of the zone of growing agrocenosis and the level of natural moisture supply in the vegetation period.

In particular, depending on the level of moisture supply in the year, plant water use for the formation of a ton of commodity products in the Polissia zone is as follows: for winter grain crops – from 350–450 m³/t in wet years to 500–550 m³/t in dry years, spring grain crops – from 375–435 m³/t to 500–530 m³/t, industrial crops – from 480–615 m³/t to 685–720 m³/t (Table 4). Thus, the level of plant water use increases 1.2–1.3 times in dry years, that is determined by more intensive evapotranspiration processes. Such conditions are

Table 4. Coefficients of crop water use in the Polissia zone of Ukraine depending on moisture supply in the year, m³/t

Crop	Wet year	Medium year	Dry year
Winter wheat	350–450	450–500	500–525
Winter rye	400–425	425–450	450–550
Spring wheat	400–435	435–465	465–500
Spring barley	375–425	425–500	500–530
Corn for grain	265–335	335–375	375–395
Sunflower	480–615	615–685	685–720
Winter rapeseed			

characteristic of growing the basic field crops in the water catchment area of the Sluch river.

In the Forest Steppe zone, crop water use per unit of product increases 1.30–1.45 times, in particular: winter grain crops – 1.30–1.40 times, spring grain crops – 1.40–1.45 times, corn for grain – 1.38–1.40 times, industrial crops – 1.30–1.40 times. In turn, agrocenosis water use rises 2 times in the Steppe zone.

Reference coefficients of plant water use (m^3/t), established according to moisture conditions of the year (m^3/ha) and statistical data on productivity (t/ha), allow calculating the volumes of green water use for growing agricultural crops in the region's crop rotations. Calculation of green water use in growing basic the field crops within the Sluch river basin was performed using the data of the State Statistics Service of Ukraine (https://www.ukrstat.gov.ua/). The values of crop productivity in Khmelnytskyi and Zhytomyr regions, whose agro-landscapes comprise the water catchment area of the Sluch river, were averaged. Statistical data on productivity and green water use of the basic field crops depending on climatic characteristics of the year are given in Table 5 (see p. 177).

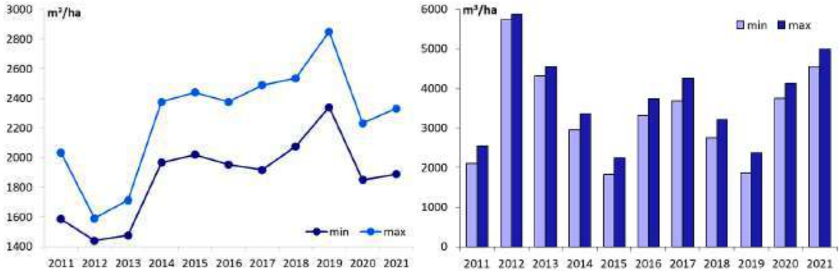
The obtained results allow outlining the level of fluctuations of changes in green water use for the formation of productivity of certain agricultural crops, determining green water use (m^3/ha) for other agricultural needs and hydro-functioning of the water catchment area. Cyclicity of an increase in crop water use (Fig. 9, *a* (see p. 178)) depending on climatic conditions of a certain year was established (Fig. 8).

The value of water use was calculated according to the ratio of saturation of crop rotation with grain and industrial crops in the research region (65 : 35%). Under conditions of dynamic changes in precipitation and a continual increase in the air temperature over the past 11 years, the largest volume of green water use for growing the basic field crops within the water catchment area of the Sluch rivers was registered in 2019: from 2,340 m^3/ha to 2,850 m^3/ha, and the minimum value was registered in 2012, 2013 and 2021 – 1,440–1,590 m^3/ha,

Table 5. Productivity (t/ha) and green water use (m^3/ha) of the basic field crops within the Sluch river basin in 2011–2021

Year		**Crops**					
		Wheat	**Spring barley**	**Winter rye**	**Corn for grain**	**Sunflower**	**Winter rapeseed**
2011	t/ha	3.2–4.5	2.5–3.3	1.9–2.9	6.6–7.8	1.8–2.0	1.5–2.2
	m^3/ha	1,636–2,288	1,303–1,700	955–1,445	2,541–3,007	1,230–1,413	1,040–1,554
2012	t/ha	3.5–4.3	3.0–3.7	2.2–2.7	7.3–7.4	1.9–2.0	2.3–2.4
	m^3/ha	1,380–1,720	1,196–1,464	890–1,121	2,187–2,229	1,047–1,091	1,282–1,293
2013	t/ha	3.2–4.2	2.7–3.3	2.0–2.7	7.9–8.9	2.2–2.3	2.5–2.8
	m^3/ha	1,292–1,672	1,080–1,304	832–1,108	2,376–2,664	1,206–1,255	1,343–1,551
2014	t/ha	4.1–5.5	3.8–4.7	2.5–3.6	7.8–8.3	2.2–2.7	2.7–3.4
	m^3/ha	1,933–2,627	1,750–2,181	1,082–1,586	2,780–2,939	1,456–1,775	1,781–2,217
2015	t/ha	4.5–5.8	4.0–4.7	2.8–3.9	5.3–6.0	2.6–2.9	2.6–3.3
	m^3/ha	2,309–2,996	2,060–2,431	1,420–1,935	2,056–2,325	1,793–2,004	1,800–2,348
2016	t/ha	4.7–5.8	3.9–4.9	2.8–4.8	7.3–7.8	2.6–3.2	1.9–2.9
	m^3/ha	2,214–2,736	1,810–2,273	1,240–2,094	2,584–2,780	1,716–2,087	1,261–1,853
2017	t/ha	4.3–6.2	3.5–5.3	2.8–5.7	6.6–7.8	2.4–3.1	3.0–3.2
	m^3/ha	2,052–2,945	1,625–2,454	1,235–2,501	2,343–2,773	1,554–2,015	1,944–2,093
2018	t/ha	4.3–5.7	3.3–4.5	2.5–4.4	9.2–9.9	2.5–3.2	2.7–3.3
	m^3/ha	2,043–2,684	1,537–2,093	1,113–1,945	3,270–3,511	1,638–2.054	1,749–2,171
2019	t/ha	4.3–4.7	3.5–4.3	3.2–4.0	6.5–7.9	2.4–3.2	2.2–2.8
	m^3/ha	2,215–2,420	1,680–2,065	1,600–2,000	2,505–3,045	1,690–2,250	1,550–1,970
2020	t/ha	4.9–5.9	3.7–4.5	3.4–4.4	8.4–9.8	2.5–3.3	2.8–3.2
	m^3/ha	2,330–2,805	1,670–2,030	1,480–1,920	2,940–3,430	1,625–2,145	1,820–2,080
2021	t/ha	5.0–6.4	4.1–4.7	3.6–5.2	8.2–11.2	2.8–3.8	3.0–3.6
	m^3/ha	2,000–2,560	1,720–1,975	1,490–2,160	2,450–3,360	1,540–2,100	1,650–1,980

1,475–1,715 m³/ha and 1,890–2,330 m³/ha, respectively. In the dry years of 2011, 2015 and 2019 characterized by precipitation deficit, accumulation of green water (m³/ha) in the water catchment area ranged from 1,830 m³/ha to 2,545 m³/ha (Fig. 9, *b*). In the wet years of 2012, 2013 and 2021, this index equaled 4,315–5,875 m³/ha. It was established that the share of using rainwater by agrocenoses in the dry years was 38.4–60.5%, in the semi-dry years – 31.0–48.0%, in the wet years – 19.7–34.0%. The total volume of green water use in the river basin landscapes in the calculation of the farmland share (39.7% (549.05 thous. ha)) was 1,005–1,565 mln m³ in 2011–2021, in the dry years – 1,110–1,565 mln m³, in the semi-wet years – 1,015–1,390 mln m³, in the wet years – 790–1,280 mln m³. The proposed approach and the results of the calculation should be used for identifying the tendencies in green water use in growing the basic field crops of a certain region. The proposed approach does not consider the course of plant vegetation development and spatio-temporal changes in evapotranspiration processes in crop cultivation within the water catchment area. Therefore, thorough calculation of water footprint should be performed on the basis of the data on natural moisture supply and water use in the plant vegetation period taking into consideration evapotranspiration processes.



a *b*

Figure 9. Balance of green water use by agricultural crops within the Sluch river basin:

a – the average of water use coefficient per hectare (m³/ha);
b – accumulation of green water (m³/ha) for maintaining water-balance stability of the river basin

Differentiation of water footprint in growing the basic field crops and calculation of the volume of moisture accumulation within the Sluch river basin

Winter crops have 2 periods of active vegetation: autumn (45–50 days: the end of September – the end of November) and spring-summer (75–100 days: the end of March – the beginning of July). Between these periods, plants are in the state of dormancy. The entire vegetation period of winter wheat lasts from 180 to 215 days. The vegetation period of spring grain crops is shorter than that of winter crops: spring barley – 80–105 days (the beginning of March – the end of June), spring wheat – 85–105 days (the beginning of March – the beginning of July), the amount of nutrition elements used for yield formation in both of them is nearly identical. The root system of spring grain crops is weaker, and the process of tillering is worse. These peculiarities should be taken into consideration in order to maintain full-blown plant nutrition throughout the vegetation period. The vegetation period of sunflower lasts 100–120 days on average (the end of April, the beginning of May – the end of August, the beginning of September). The vegetation period of winter rapeseed (autumn and spring-summer) lasts 180–225 days (the end of August – the beginning of July). The duration of the vegetation period of corn for grain in the Polissia zone ranges from 150 to 170 days (the end of April and the beginning of May – the end of August and the beginning of September). These periods should be taken into account to specify the crop coefficient (K_c) and adjust calculation of crop evapotranspiration (ET_c) and water footprint (WF). High temperatures accelerate crop maturation and reduce the duration of the vegetation period by 8.0–24.0%, increase evapotranspiration processes and decrease the level of soil moisture. In the vegetation period, agricultural crops are supplied with moisture to 60–70% by precipitation, to 30–40% – by soil moisture reserves. This regularity should be taken into consideration when calculating water footprint which consists of “green” and “blue” water resources, i.e. “rain” and “soil or surface” water that evaporates in growing agricultural crops.

According to the generalized FAO data, the duration of the main phenological stages of plants belonging to the basic field crops and similar growing conditions within the Sluch water catchment area are as follows: for winter wheat with the vegetation period of 180 days, including L_{ini} – 20 days, L_{dev} – 60 days, L_{mid} – 70 days, L_{late} – 30 days; winter rye – no available data; spring wheat and barley with the vegetation period of 120 days, including L_{ini} – 15 days, L_{dev} – 25 days, L_{mid} – 50 days, L_{late} – 30 days; grain for corn with the vegetation period of 125 days, including L_{ini} – 20 days, L_{dev} – 35 days, L_{mid} – 40 days, L_{late} – 30 days; sunflower with the vegetation period of 130 days, including L_{ini} – 25 days, L_{dev} – 35 days, L_{mid} – 45 days, L_{late} – 25 days; winter rapeseed – no available data. The given data do not correspond to the exact characteristics of the vegetation period and phenological stages of the development of the basic field crops for the research territory. Therefore, Table 5 gives the duration of phenological development stages of agricultural crops and sowing dates in accordance with climatic conditions of the water catchment area of the Sluch river.

Due to an increase in the air temperature and erratic precipitation over the past years, new climatic conditions for growing agricultural crops and volumes of water use are forming. Therefore, research and calculation of the volumes of green and blue water use were performed using the example of new conditions for climate formation with different levels of moisture supply and evapotranspiration processes, in particular: 2019 – a dry year with a high level of evapotranspiration ($P = 741$ mm, $T = 9.4$ °C, $ET_o = 2.12$ mm/day); 2020 – a semi-wet year ($P = 595$ mm, $T = 9.3$ °C, $ET_o = 2.09$ mm/day); 2021 – a wet year with a low level of evapotranspiration ($P = 690$ mm, $T = 7.4$ °C, $ET_o = 1.95$ mm/day).

For calculating the volumes of water footprint, the vegetation periods of the basic field crops in 2018–2021 (Table 6, see p. 181–182) were selected. Winter crops: 2018–2019 – a semi-wet year grows into a dry year; 201922020 – a dry year grows into a semi-wet year; 2020–2021 – a semi-wet year grows into a wet year.

Fig. 10 (see p. 183) presents distribution of the values of climate characteristics in the vegetation periods of 2018–2021 for establishing

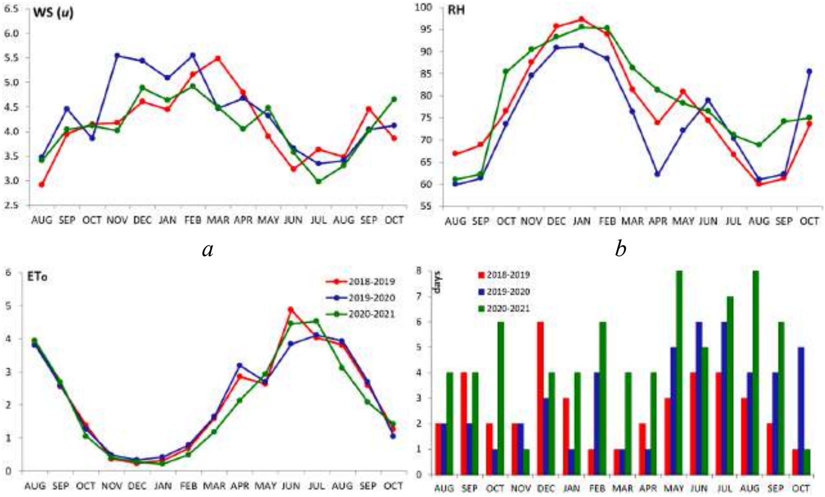
Table 6. Characteristics of the vegetation dates of the basic field crops under climatic conditions of the Sluch river basin

Crop		**Vegetation dates**			**Duration of the main phenological stages of plant development, days**				
		Wet year	**Semi-wet year**	**Dry year**	**Year characteristics**	L_{ini}	L_{dev}	L_{mid}	L_{late}
1		**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Winter wheat	Sowing dates (day, month)	15–20.09	15–20.09	20–25.09	Wet	95	80	20	20
	Harvesting dates (day, month)	20–25.07	15–20.07	10–15.07	Semi-wet	90	75	18	15
	Vegetation period (days)	215	198	180	Dry	85	70	10	15
Winter rye	Sowing dates (day, month)	25.08–01.09	20.08–05.09	01–10.09	Wet	110	80	15	20
	Harvesting dates (day, month)	20–25.07	20–25.07	10–20.07	Semi-wet	100	75	15	15
	Vegetation period (days)	225	205	185	Dry	90	70	10	15
Spring wheat	Sowing dates (day, month)	01–05.04	25.03–01.04	20–25.03	Wet	35	30	25	15
	Harvesting dates (day, month)	25–28.07	25–30.07	15–25.07	Semi-wet	30	30	20	15
	Vegetation period (days)	105	95	85	Dry	30	25	20	10

End of Table 6

1		2	3	4	5	6	7	8	9
Spring barley	Sowing dates (day, month)	01–05.04	25.03–01.04	20–25.03	Wet	35	30	25	15
	Harvesting dates (day, month)	25–28.07	25–30.07	15–25.07	Semi-wet	30	30	20	15
	Vegetation period (days)	105	95	80	Dry	30	20	20	10
Corn for grain	Sowing dates (day, month)	10–15.05	05–10.05	25.04–02.05	Wet	45	45	50	30
	Harvesting dates (day, month)	15–20.10	10–15.10	01–10.10	Semi-wet	50	45	45	25
	Vegetation period (days)	170	165	155	Dry	50	45	40	20
Sunflower	Sowing dates (day, month)	10–15.05	05–10.05	25.04–2.05	Wet	50	35	15	20
	Harvesting dates (day, month)	20–25.09	15–20.09	05–15.09	Semi-wet	45	30	15	18
	Vegetation period (days)	120	108	105	Dry	45	30	15	15
Winter rapeseed	Sowing dates (day, month)	10–15.08	15–20.08	25.08–01.09	Wet	125	50	30	20
	Harvesting dates (day, month)	15–20.07	05–10.07	01–05.07	Semi-wet	120	40	25	15
	Vegetation period (days)	225	200	185	Dry	115	35	20	15

and adjusting the crop coefficient value (*Kc*) using the method FAO Penman-Monteith ET_o (https://www.fao.org/3/X0490E/x0490e0b.htm#TopOfPage). The research period involves the vegetation periods of the basic field crops within the Sluch river basin.



a *b*

c *d*

Figure 10. Distribution of the values of climate characteristics in the vegetation periods of 2018–2021 for establishing and adjusting the crop coefficient value (*Kc*) in accordance with the method FAO Penman-Monteith ET_o:
a – wind speed, m/c; *b* – air humidity, %;
c – the value of reference evapotranspiration, mm/day;
d – precipitation in the form of rain and snow, days

Given the climate characteristics of the region and conditions of a certain year of crop cultivation, the crop coefficients (*Kc*) were determined according to plant water use at certain phenological stages (Table 7, see p. 184–186). The proposed coefficients were used for calculating the values of crop evapotranspiration (ET_c) and spatio-temporal modelling of water footprint volumes, determining the portion of green water use according to climate characteristics of a certain year and a typical structure of crop rotation within the agrolandscapes of the Sluch river basin.

Table 7. Distribution of the *Kc* values in the vegetation period of the basic field crops under climatic conditions of the Sluch river basin

Tears	Crops	Months														
		AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
The value of the crop coefficient (*Kc*)																
2018–2019	Winter wheat		0.45	0.50	0.50	0.50	0.50	0.50	0.63	0.84	1.06	1.17	0.25			
	Winter rye	0.20	0.45	0.50	0.50	0.50	0.50	0.50	0.63	0.84	1.06	1.17	0.25			
	Spring wheat								0.35	0.67	0.71	1.17	0.25			
	Spring barley								0.35	0.67	0.71	1.17	0.25			
	Corn for grain										0.38	0.53	0.80	1.12	1.35	0.35
	Sunflower										0.38	0.53	0.80	1.11	0.35	
	Winter rapeseed	0.20	0.45	0.50	0.50	0.50	0.50	0.50	0.64	0.85	0.97	1.02	0.35			
2019–2020	Winter wheat		0.30	0.50	0.50	0.50	0.50	0.50	0.63	0.93	1.10	1.21	0.25			
	Winter rye		0.30	0.50	0.50	0.50	0.50	0.50	0.63	0.93	1.10	1.21	0.25			
	Spring wheat								0.35	0.78	0.84	1.21	0.25			
	Spring barley								0.35	0.78	0.84	1.21	0.25			
	Corn for grain										0.50	0.51	0.76	1.11	1.33	0.35
	Sunflower										0.50	0.51	0.76	1.10	0.35	
	Winter rapeseed	0.20	0.30	0.50	0.50	0.50	0.50	0.50	0.71	0.95	1.00	1.01	0.35			

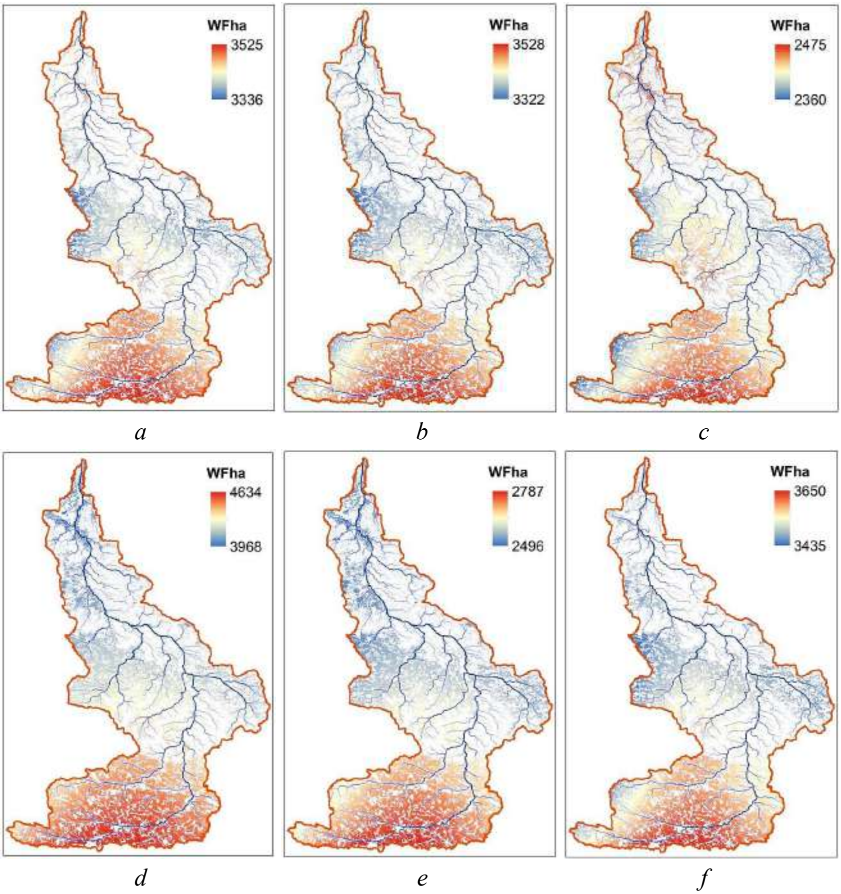
Continuation of Table 7

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2020–2021	Winter wheat		0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.71	1.06	1.21	0.25			
	Winter rye	0.20	0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.71	1.06	1.21	0.25			
	Spring wheat									0.30	0.82	1.21	0.25			
	Spring barley									0.30	0.82	1.21	0.25			
	Corn for grain										0.50	0.53	0.73	1.06	1.25	0.35
	Sunflower										0.50	0.53	0.73	1.06	0.35	
	Winter rapeseed	0.20	0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.71	0.97	1.03	0.35			
The value of the crop evapotranspiration (ET_c), mm/day																
2018–2019	Winter wheat		1.15	0.69	0.18	0.12	0.16	0.35	1.00	2.39	2.79	5.70	1.01			
	Winter rye	0.79	1.15	0.69	0.18	0.12	0.16	0.35	1.00	2.39	2.79	5.70	1.01			
	Spring wheat								0.56	1.91	1.87	5.70	1.01			
	Spring barley								0.56	1.91	1.87	5.70	1.01			
	Corn for grain										1.00	2.58	3.22	4.27	3.50	0.44
	Sunflower										1.00	2.58	3.22	4.23	0.91	
	Winter rapeseed	0.79	1.15	0.69	0.18	0.12	0.16	0.35	1.02	2.42	2.55	4.97	1.41			

End of Table 7

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2019–2020	Winter wheat		0.78	0.63	0.24	0.17	0.21	0.39	1.03	2.97	2.97	4.65	1.03			
	Winter rye		0.78	0.63	0.24	0.17	0.21	0.39	1.03	2.97	2.97	4.65	1.03			
	Spring wheat								0.57	2.49	2.27	4.65	1.03			
	Spring barley								0.57	2.49	2.27	4.65	1.03			
	Corn for grain										1.35	1.96	3.12	4.36	3.58	0.37
	Sunflower										1.35	1.96	3.12	4.32	0.94	
	Winter rapeseed	0.76	0.78	0.63	0.24	0.17	0.21	0.39	1.16	3.03	2.70	3.88	1.44			
2020–2021	Winter wheat		1.08	0.53	0.20	0.14	0.11	0.25	0.59	1.51	3.11	5.40	1.13			
	Winter rye	0.79	1.08	0.53	0.20	0.14	0.11	0.25	0.59	1.51	3.11	5.40	1.13			
	Spring wheat									0.64	2.40	5.40	1.13			
	Spring barley									0.64	2.40	5.40	1.13			
	Corn for grain										1.47	2.36	3.31	3.31	2.60	0.49
	Sunflower										1.47	2.36	3.31	3.31	0.73	
	Winter rapeseed	0.79	1.08	0.53	0.20	0.14	0.11	0.25	0.59	1.51	2.84	4.59	1.59			

It was found that the average volume of water footprint in the vegetation period of 2018–2021 in the agro-landscapes of the water catchment area (Fig. 11) for winter wheat was 3,336–3,525 m^3/ha, winter rye – 3,322–3,528 m^3/ha, spring barley and wheat – 2,360–2,475 m^3/ha, corn for grain – 3,968–4,634 m^3/ha,



a *b* *c*

d *e* *f*

Figure 11. Spatial differentiation of water footprint (*WFha*, m^3/ha) in growing the basic field crops in the vegetation periods of 2018–2021: *a* – winter wheat; *b* – winter rye; *c* – spring barley and wheat; *d* – corn for grain; *e* – sunflower; *f* – winter rapeseed

sunflower – 2,496–2,787 m^3/ha, winter rapeseed – 3,435–3,650 m^3/ha. The registered zonal peculiarities of spatial distribution of the volume of water use are characterized by its rise in the upper part of the river basin due to an increase in evapotranspiration processes by 5.0–17.0%. Such processes result in a reduction in the volume of green water accumulation for maintaining the hydro-functioning of the upper courses of the Sluch river.

Table 8 (see p. 189) presents calculations of water footprint dynamics in growing the basic field crops in the vegetation periods of 2018–2021. The ratio of green water use for transpiration and growing the basic field crops (*WUha*, m^3/ha; *WUt*, m^3/t) and evaporation of soil (blue) moisture (*Eha*, m^3/ha; *Et*, m^3/t) were established. The portion of green water distribution varies depending on climatic conditions, crop rotation, vegetation periods and crop productivity. The value of water use per 1 ha (*WUha*, m^3/ha) involves water use for plant development and transpiration from the plant surface. In particular, the *WUha* value depends on climatic condition of the year, crop yields (*AY*, t/ha) and water use per 1 ton of products (*WUt*, m^3/t).

Relatively high values of water footprint (*WFha*) per 1 ha were registered in growing corn for grain – from 4,159 m^3/ha to 4,203 m^3/ha and winter crops, including: winter wheat – 3,294–3,628 m^3/ha, winter rye – 3,335–3,594 m^3/ha and winter rapeseed – 3,325–3,770 m^3/ha. In particular, relatively low values of *WFha* are characteristic of crops with a short vegetation period, including: spring barley – 2,230–2,530 m^3/ha and sunflower – 2,500–2,850 m^3/ha. Yields (*AY*, t/ha) and water footprint (*WUt*) depending on climate characteristics of the year of agrocenosis vegetation are an important feature of the total volume of green water use and calculation of the volume of evaporated soil moisture. High values of *WFt* are registered in industrial crops – 864–1,330 m^3/t, low values of *WFt* are characteristic of corn for grain – from 429 m^3/t to 584 m^3/t and spring barley – 572–609 m^3/t. Therefore, saturation of crop rotation with industrial crops causes an increase in the volumes of water footprint 1.5–2.3 times and evaporation of soil (blue) moisture – 1.3–4.0 times. A considerable portion of the volume of evaporated soil (blue) moisture (*Et/WFt*) is registered under winter rye and winter rapeseed – from 0.45 to 0.53. It characterizes a high level of green water use, low productivity of crop cultivation and a lack of their agro-ecological efficiency in creating optimal models

Table 8. The average of water footprint dynamics in growing the basic field crops in the vegetation periods of 2018–2021

Crop		**Vegetation period**								
		AY, t/ha	**WFha, m^3/ha**	**WUha, m^3/ha**	**Eha, m^3/ha**	**WFt, m^3/t**	**WUt, m^3/t**	**Et, m^3/t**	**WUt/WFt**	**Et/WFt**
Winter wheat	2018–2019	4.5	3,294	2,318	976	732	515	217	0.70	0.30
	2019–2020	5.4	3,628	2,568	1,060	672	476	196	0.71	0.29
	2020–2021	5.7	3,354	2,280	1,074	588	400	188	0.68	0.32
Winter rye	2018–2019	3.6	3,335	1,800	1,535	926	500	426	0.54	0.46
	2019–2020	3.9	3,594	1,700	1,894	922	436	486	0.47	0.53
	2020–2021	4.4	3,347	1,825	1,522	761	415	346	0.55	0.45
Spring barley	2019	3.9	2,230	1,873	357	572	480	92	0.84	0.16
	2020	4.1	2,495	1,850	645	609	451	157	0.74	0.26
	2021	4.4	2,530	1,848	682	575	420	155	0.73	0.27
Corn for grain	2019	7.2	4,203	2,775	1,428	584	385	198	0.66	0.34
	2020	9.1	4,526	3,185	1,341	497	350	147	0.70	0.30
	2021	9.7	4,159	2,905	1,254	429	299	129	0.70	0.30
Sunflower	2019	2.8	2,500	1,970	530	893	704	189	0.79	0.21
	2020	2.9	2,570	1,885	685	886	650	236	0.73	0.27
	2021	3.3	2,850	1,820	1,030	864	552	312	0.64	0.36
Winter rapeseed	2018–2019	2.5	3,325	1,760	1,565	1,330	704	626	0.53	0.47
	2019–2020	3.0	3,534	1,950	1,584	1,178	650	528	0.55	0.45
	2020–2021	3.3	3,770	1,815	1,955	1,142	550	592	0.48	0.52

of using soil (blue) moisture for the research region. The given calculations show the ratio of green (*WUt/WFt*) and blue (*Et/WFt*) water use in growing certain field crops within the Sluch river basin.

Spatial differentiation of water footprint (*WFha,* m^3/ha, *WF*, m^3/vegetation) in growing agrocenoses in the vegetation periods of 2018–2021 and the volume of green water accumulation in the agro-landscapes are calculated in accordance with the ratio of saturation of crop rotations with the basic field crops within the Sluch river basin, in particular: winter wheat – 24.3%, winter rye – 1.9%, spring barley – 7.5%, corn for grain – 31.3%, sunflower – 24.8%, winter rapeseed – 10.2%. The highest *WFha* values (Fig. 12, see p. 191) were registered in the vegetation period from August, 2019 (a dry year) to October, 2020 (a semi-wet year) – from 3,385 m^3/ha to 3,739 m^3/ha. In the vegetation period from August, 2018 (a semi-wet year) to October, 2019 (a dry year), the *WFha* value equaled 3,157–3,508 m^3/ha; from August, 2020 (a semi-wet year) to October, 2021 (a wet year), the *WFha* value ranged from 3,329 m^3/ha to 3,621 m^3/ha. The total volume of water footprint (*WF*, m^3/vegetation) in growing a crop rotation of the field crops was: in 2018–2019 – 1,991 mln m^3, 2019–2020 – 2,440 mln m^3, 2020–2021 – 2,363 mln m^3.

Precipitation (*Pv*, mm) in the vegetation period of 2018–2019 within the agro-landscapes of the river water catchment area equaled 556–716 mm; in 2019–2020 – from 595 mm to 744 mm; in 2020–2021 – from 646–817 mm. The total volume of precipitation in the vegetation period within the agro-landscapes of the river water catchment area equaled: in 2018–2019 – 3,760 mln m^3, 2019–2020 – 4,423 mln m^3, 2020–2021 – 4,839 mln m^3.

Spatio-temporal regularities of a change in the portion of using precipitation by a crop rotation of the field crops in the vegetation years with different climate conditions were established on the basis of the ratio of the *WFha* and *Pv* data. In particular, in the vegetation period of 2018–2019 (semi-wet → dry) the portion of using precipitation (*WFha/Pv*, %*)* was 45.2–61.5%; in 2019–2020 (dry → semi-wet) – from 47.4% to 61.6%; in 2020–2021 (semi-wet → wet) – from 41.4% to 55.2%. The obtained results allow

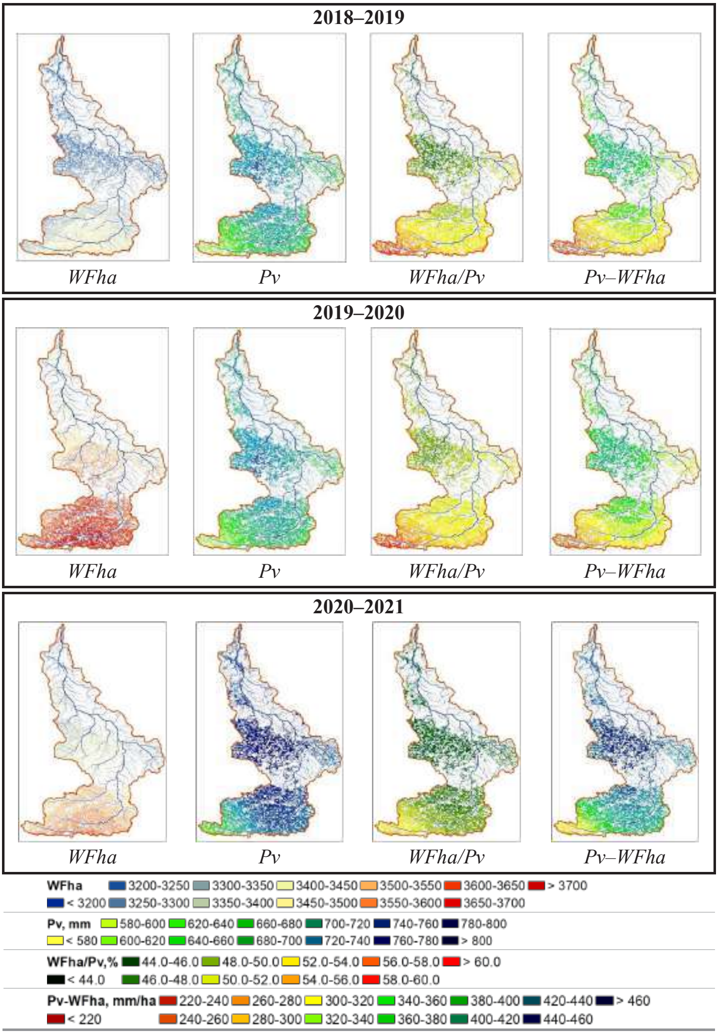


Figure 12. Balance of green water use by the basic field crops in the vegetation periods of 2018–2021:

WFha – water footprint in growing the field crops, m^3/ha, *Pv* – the total amount of precipitation in the vegetation period, mm; *WFha/Pv* – the ratio of rain (green) water use in the vegetation period, %; *Pv-WFha* – accumulation of green water in the agro-landscapes of the water catchment area, mm/ha calculating the volume of accumulation of rain (green) water (*Pv-WFha*, mm) in the agro-landscapes for maintaining the hydro-functioning of the water catchment area of the Sluch river. It was found that in the vegetation period of 2018–2019, green water accumulation after growing the basic field crops was 215–392 mm/ha; in 2019–2020 – 229–389 mm/ha; in 2020–2021 – 289–477 mm/ha. The total volume of green water accumulation in the vegetation period from the agro-landscapes for maintaining water-balance stability of the river basin was: in 2018–2019 – 1,769 mln m^3, or 47.0% from precipitation *Pv*; 2019–2020 – 1,983 mln m^3, or 44.8% from *Pv*; 2020–2021 – 2,476 mln m^3, or 51.2% from *Pv*.

The research results are of high agricultural and ecological value, since they allow adjusting and substantiating resource-saving agro-technologies and crop rotations depending on climate changes and moisture deficit, the volumes of efficient water use by an individual crop, the options of rain (green) water accumulation and retention of soil (blue) moisture for creating further favorable conditions for the vegetation of a field crop rotation. In terms of ecology, the results are important for calculating the volumes of retention and additional accumulation of moisture and establishing water balance stability of the river basin.

CONCLUSIONS

Spatio-temporal regularities of the differentiation of water footprint in growing agricultural crops and the formation of water balance stability of the Sluch river basin in the Polissia zone of Ukraine under climate change were established on the basis of the analysis of the data of Climatic Research Unit of the University of East Anglia, NASA POWER, FAO and decoding of the satellite imagery of the spacecraft Sentinel 2. A series of climate maps and maps of the balance of green water use by the basic field crops in the vegetation periods were created, that allowed conducting research on climate change, the formation of water footprint volumes depending on crop rotations and climatic conditions of the vegetation period, finding the ratio of using rain (green) water and soil (blue) moisture in the vegetation period, calculating the volumes of green water accumulation in the agro-landscapes of the water catchment area for establishing water balance stability of the Sluch river basin. It was found that over the past 120 years the amount of precipitation per year within the water catchment area of the Sluch river basin has ranged from 487 mm to 716 mm. Over the past 40 years the average annual temperature in the water catchment area has risen by 1.9 °C on average, that led to a considerable increase in evapotranspiration processes from 1.79 mm/day to 2.25 mm/day, a reduction in moisture supply in the basin landscape and aquatic territorial structures by 20–25%. The results of correlation analysis allowed establishing that the main climate component of the differentiation of reference evapotranspiration (ET_o) is air temperature (T). The level of correlation of the average annual T and ET_o values is 0.79, that of the average monthly values equals 0.95. The volumes of water footprint were calculated for the vegetation period of a crop rotation of the basic field winter and spring crops in 2018–2021, in particular: 2018–2019 – a semi-wet year grows into a dry year; 2019–2020 – a dry year grows into a semi-wet year; 2020–2021 – a semi-wet year grows into a wet year. The ratio of saturation of crop rotations in the years of the research was as follows: winter wheat – 24.3%, winter rye – 1.9%, spring barley – 7.5%, corn for grain – 31.3%, sunflower – 24.8%, winter rapeseed – 10.2%. The volumes of virtual water use and the ratio of rain (green) and soil (blue) water use were calculated for the crops of crop rotations. High saturation of crop rotations with industrial crops results in an increase in the volumes of water footprint for growing 1 ton of products – 1.5–2.3 times and evaporation of soil (blue) moisture – 1.3–4.0 times. Therefore, high saturation of crop rotations with these crops causes a low level of their agro-ecological efficiency in terms of green water accumulation and optimization of soil (blue) moisture use aimed at creating favorable conditions for water balance stability of the river basin. The ratio of "green:blue" water use for the basic field crops in the agro-landscapes of the water catchment area is as follows:

winter wheat – 0.7 : 0.3; winter rye – 0.52 : 0.48; winter rapeseed – 0.52 : 0.48; spring barley – 0.77 : 0.23; corn for grain – 0.69 : 0.31; sunflower – 0.72 : 0.28. It was established that the portion of using precipitation by a crop rotation of the field crops in the vegetation years with different climate conditions ranged from 45.2% to 61.5% in 2018–2019 (semi-wet → dry); in 2019–2020 (dry → semi-wet) – from 47.4% to 61.6%; in 2020–2021 (semi-wet → wet) – from 41.4% to 55.2%. It caused heterogeneity of additional accumulation of green water in the agro-landscapes for maintaining water balance stability of the river basin at the following level: in 2018–2019 – 1,769 mln m^3, or 47.0% from precipitation (Pv); 2019–2020 – 1,983 mln m^3, or 44,8% from Pv; 2020–2021 – 2,476 mln m^3, or 51.2% from Pv. The proposed research scheme and the obtained results are important for adjusting and substantiating resource-saving agro-technologies and crop rotations in accordance to climate changes, establishing water balance stability of the river basin through the index of additional accumulation of green water.

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THE INFLUENCE OF GROWTH-REGULATING AGENTS ON THE YIELD OF SUNFLOWER HYBRIDS IN THE STEPPE ZONE OF UKRAINE: ANALYSIS AND FORECAST

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INTRODUCTION

Application of the technology of Earth remote sensing is a promising trend in agricultural science in the area of research on extreme conditions of agriculture (Lisetskii et al., 2016; Dudiak et al., 2019a; Wang et al., 2019; Dikshit et al., 2021). Research on the state of crops on the basis of a normalized difference vegetation index (NDVI) (Ouzemou et al., 2018; Casa et al., 2021; Tenreiro et al., 2021) entailing further improvement of agro-technological measures for growing agricultural crops is highly topical. Spatio-temporal investigation of differentiation of a vegetation index of agrocenoses is a main indicator of plant development at different phenological stages (Balaghi et al., 2008; Zhang et al., 2022), that allows evaluating the level of the efficiency of agro-technological measures (Congcong et al., 2019), establishing the impact of irrigation on natural-climatic conditions (Assan et al., 2020; Pichura et al., 2023a), examining adaptive properties of varieties and hybrids (Roznik et al., 2022). In particular, information of satellite images, used for forecasting agricultural crop yields, is studied through detailed analysis of seasonal changes in the values of a normalized difference vegetation index (Nagy et al., 2018; Shammi et al., 2021).

Modelling of relationships between the state of agrocenoses cover and activeness of photosynthetic processes reflected in the level of chlorophyll production at certain phenological stages is possible due to identification of spectral reflectance characteristics of plants (Tucker et al., 2020; Matas-Granados et al., 2022). It allows establishing the level of variety and hybrid plasticity in certain natural-climatic conditions, making it possible to correct technologies for growing agricultural crops through improving complexes of agro-technological measures optimizing sowing dates, select the most effective growth-regulators and fertilizers (Domaratskiy et al., 2018, 2020, 2021, 2022).

Methods of expert visual assessment of field conditions (Amir et al., 1990; Diskin, 1999), statistical processing of field research (Sadras et al., 2015), comparison by similar years (Murphy et al., 1991; Park et al., 2005), dispersion analysis and regression modelling (Ansarifar et al., 2021; Hayat et al., 2022) are mainly used for forecasting agricultural crop yields. Against a background of the development of modern tools and technologies of Earth remote sensing, the method of decoding space imagery on the basis of a NDVI is still efficient and promising. It is the most informative and reliable method for forecasting acrocenoses productivity. Efficiency of using a NDVI is proved in the studies on the state of forests (Lisetskii et al., 2017; Berveglieri et al., 2021), in examining the structure of crops and establishing the intensity of agricultural crop growth (Lunetta et al., 2010; Marino, 2023), performing spatial cluster analysis of landscape structures (Petrosillo et al., 2022; Du et al., 2023), areas of vegetated coastal territories and the intensity of algal bloom (Pichura et al., 2017, 2018), identifying desertification and saline lands (Breus et al., 2019, 2020; Dudiak et al., 2019b, 2020, 2021) etc. The advantages of using a NDVI are moderate sensitivity to changes in soil and atmospheric background and accurate identification of photosynthetic activeness of plants.

The main aim of forecasting crop yields is to increase the level of profitability of agriculture, food security of the region and the country due to substantiation of an appropriate complex of agro-technological measures, selection of plastic varieties and hybrids for growing in suitable soil-climatic conditions. Therefore, identification of the state of crops at different plant growth stages on the basis of a NDVI is a reliable instrument for forecasting crop yields. Air temperature and the level of moisture content are important abiotic factors (Pichura et al., 2020, 2022) of the formation of agricultural crop yields. It is necessary to highlight that moisture content in a pre-sowing period and in the plant growing season is a key factor of crop productivity in the Steppe zone of Ukraine. Therefore, volume and quality of crop yields depend on the level of moisture content at critical stages of the growing season. Water uptake by plants at certain critical phenological stages mainly determines volumes of crop yields.

The level of water uptake and absorption of nutrients changes during the growing season of sunflower plants, for instance, plants consume about 20% of moisture from sprouting to capitulum formation; at the phenological stages of capitulum formation and flowering, consumption of total moisture is 60% (Domaratskiy et al., 2021). Therefore, it is possible to create a model for forecasting sunflower productivity on the basis of a NDVI and information about distribution of the share of water uptake during the growing season and absorption of nutrients by plants at different stages of plant growth. It is important to take into consideration genetic features and plasticity of plants of different varieties and hybrids in response to the climatic conditions of the Steppe in order to complete the model for forecasting and make it reliable.

The purpose of the research is to establish spatio-temporal regularities of differentiation of a vegetation index in order to forecast sunflower hybrid productivity in the soil-climatic zone of the Steppe.

MATERIAL AND METHODS

Area of research. The research on development and productivity of different sunflower hybrids in natural-climatic conditions of the Steppe zone of Ukraine was conducted in 2019–2021 in the research field of Mykolaiv State Agricultural Research Station of the Institute of Irrigated Agriculture of the National Academy of Agricultural Sciences (the SARS IIA of the NAAS) of Ukraine (Fig. 1, see p. 205). The experiments were carried out without irrigation.

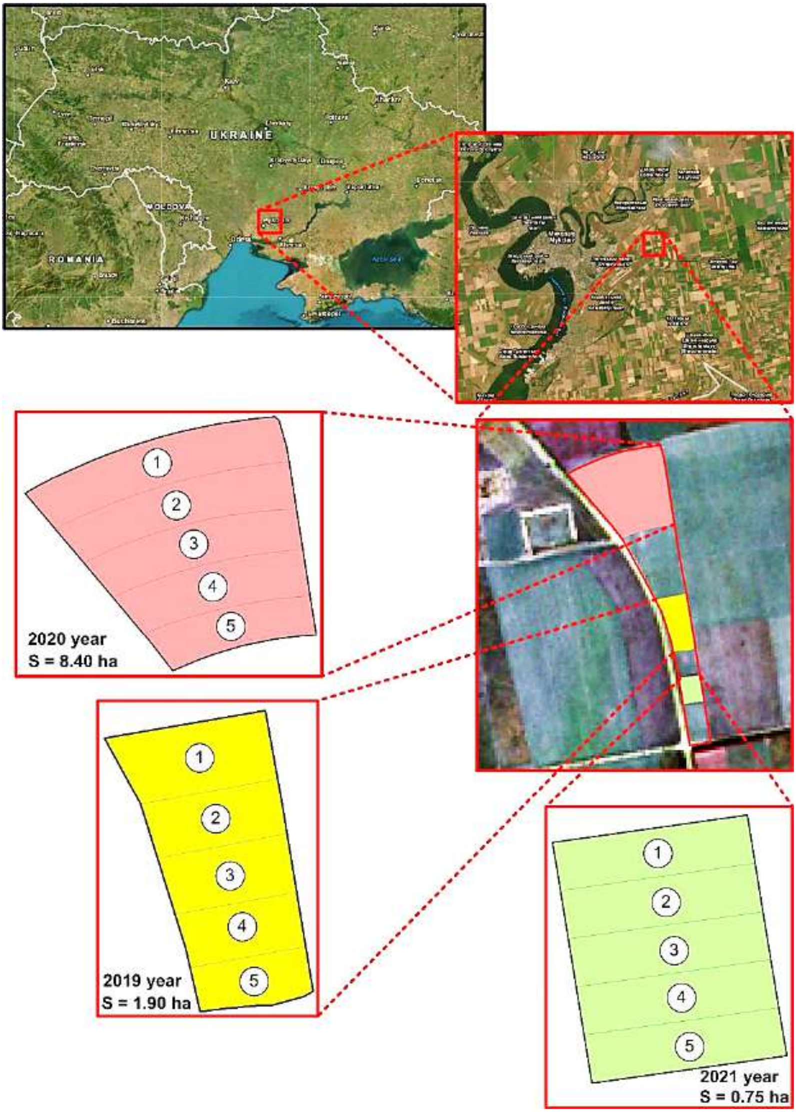


Figure 1. Location of the research fields and placement of sunflower hybrid crops in 2019–2021:
1 – Oplot; 2 – Hector; 3 – DSL403; 4 – P64HE133; 5 – 8KH477KL

The total area of the experiments: in 2019 – 1.9 ha, in 2020 – 8.4 ha and in 2021 – 0.75 ha. Location of the research fields and placement of sunflower hybrid crops: in 2019 – N 46°98'16.4'' E 32°14'57.0'', in 2020 – N 46°98'51.5'' E 32°14'38.7'', in 2021 – N 46°97'83.3'' E 32°14'67.5''

The research plots were located on southern black soils, poor in humus content, with dusty, heavy loamy granulometric composition. Humus content in soils ranges from 2.7 to 3.1%, the depth of a humus horizon is 30–40 cm. The reaction of soil solution is close to neutral (pH 6.5–6.8), hydrolytic acidity ranges from 2.00 to 2.52 mg equiv. per 100 g of soily. The sum of absorbed alkali equals 32–35 mg equiv. per 100 g of soil, the degree of saturation with alkali equals 95.7%. In terms of the content of mobile elements, the soil of the research plot is characterized by a medium content of nitrate nitrogen in the soil layer of 0–20 cm – 30.0 mg/kg, the content of mobile phosphorous – 100 mg/kg and a very high content of exchangeable potassium – 300.0 mg/kg of soil.

The research used the actual values of the surface air temperature (T, °C), the total precipitation (P, mm) during the growing season in the years of 2019, 2020 and 2021 (the meteorological station in Mykolaiv). The climatic norms for the research area were calculated using the data of 1970–2020.

Program of scientific research. A two-factor field experiment was designed: Factor A – sunflower hybrid with high oil content of Ukrainian and foreign breeding, Factor B – foliar treatment of plants with multifunctional growth-regulators with antifungal properties.

Factor A – the Ukrainian breeding included the sunflower hybrids Hector and Oplot (its originator – the Plant Production Institute named after V. Ya. Yuriev), the foreign breeding – DSL403 and P64HE133 (their producer – Corteva, Brevant) and 8KH477KL (its producer – Dow Seeds).

Factor B – the multifunctional growth-regulators of chemical origin Architect™ (the identification number is 30652554/SDS_CPA_UA/UK) and of biological origin – Helafit Combi (the registration certificate is UA № A07743 dated September 2, 2019). The plots under each hybrid were divided into three parts: 1 – the preparation Architect™, 2 – the preparation Helafit Combi, 3 – control without application of preparations, plants were treated with pure water. The preparations were applied at the rate of 1 l/ha as foliar treatment at the stage of the formation of 6–8 true leaves (BBCH 16–18) of the macro-stage of "leaf formation". It is necessary to highlight that multi-functionality of the preparations is determined by growth-regulating properties and antifungal effect. The plants were treated with a backpack sprayer until 11 a. m. when it was not windy. The plants of the control variant were treated with pure water.

The experiments were replicated three times (in 2019, 2020 and 2021). In 2019 the sowing date was April, 24, the harvest date was August, 26, in 2020 the sowing date was April, 29, the harvest date was August, 22, in 2021 the sowing date was May, 10, the harvest date was September, 12. Annually sunflower hybrids were placed with the same sequence (Fig. 1) under typical soil and climatic conditions, winter wheat was a pre-crop. The crop area of the first order plot equaled 168 m^2, the registered plot was 120 m^2.

Seeds were planted with the precision seed drill UPS-8, the seeding rate was 48.7 thous. pcs/ha. All the registrations and observations were made in compliance with the methodology of scientific research in agronomy (Ermantraut et al., 2008, Didora et al., 2013), the methodological recommendations of the Institute of Plant Production named after V. Ya. Yuriev of the NAAS (Kyrychenko et al., 2014), the available DSTU 7011:2009 "Sunflower. Specifications" (DSTU 7011:2009 …) and DSTU 6068:2008 "Sunflower seeds. Varietal and seeding characteristics. Specifications" (DSTU 6068:2008 …). Soil moisture was measured with a thermostat-measuring method in the course of seeding and harvesting (Papish, 2001). The seed yields were registered manually, with further recalculation of the yields as tons per hectare of the crop area with the seed moisture of 8% and the seed purity of 100%.

Methods for decoding space imagery and spatial analysis. Spatio-temporal differentiation of sunflower hybrid vegetation was determined on the basis of the calculation of a normalized difference vegetation index (NDVI) (Essaadia et al., 2022; Ding et al., 2022; Beyer et al., 2023) using the data of the decoded space imagery of Sentinel 2 with the spatial resolution of 10 × 10 m per pixel.

The value of *NDVI* was calculated by the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}, \tag{1}$$

where *NIR* – visible and near infrared band (Sentinel 2 – Band 8); *Red* – red band of electromagnetic spectrum (Sentinel 2 – Band 4).

The value of *NDVI* ranges from 0 to 1.0. Uncovered soil is characterized by the values of *NDVI* from 0.05 to 0.15. The value of *NDVI* at the beginning of seeding in all the years of the research was 0.15. In the period of the active plant growth, from the macro-stage "development of flower buds" (BBCH 51–59) and to the end of the macro-stage "flowering" (BBCH 61–69), the value of *NDVI* reflects the state of the crop development, in particular: <0.15 uncovered soil; 0.15–0.2 – thin vegetation; 0.2–0.3 – stunted vegetation; 0.3–0.4 – very poor state; 0.4–0.55 – satisfactory state; 0.55–0.7 – good state; >0.7 – very good state of plants.

Space images without clouds over the research field were used in the research. The frequency of image processing was 10–16 days, that allowed determining the values of *NDVI* for the basic phenological stages of sunflower hybrid development, in particular: sprouts (BBCH 00–09), the first pair of true leaves (BBCH 10–12), capitulum formation (BBCH 14–59), flowering (BBCH 61–69) and maturation (BBCH 71–99). Correspondence of each value of *NDVI* to a phenological stage allowed observing the process of the development of sunflower hybrid crops and identifying changes in the dates of the plant phenological stages in accordance with the natural-climatic conditions: a dry, medium-wet and wet year. The space images were processed taking into consideration the sowing and harvest dates in 2019, 2020 and 2021.

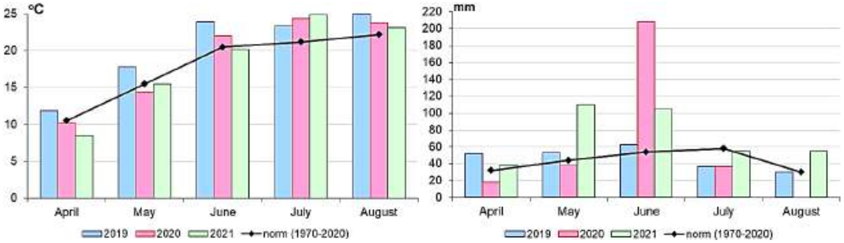
In order to improve the quality of map visualization of spatio-temporal distribution of the values of *NDVI* and increase reliability of interpretation of a vegetation index within certain areas and characteristics of vegetation heterogeneity of sunflower hybrid crops, we interpolated the values obtained on the basis of decoding the space imagery of Sentinel 2. Interpolation was performed using the method of geostatic analysis of a radial basis function (Kamińska et al., 2014; Pichura et al., 2023b). This deterministic method allows establishing accurate interpolated surface of a change in the values of *NDVI* and storing the initial raster data. The correlation-regression method (Riffenburgh, 2006) was used to develop functions for predicting the yield of sunflower hybrids depending on the spatio-temporal differentiation of the values of the vegetation index.

We processed space images, made maps and performed spatio-temporal analysis using the licensed software ArcGis 10.6.

RESULTS AND DISCUSSION

Analysis of the climatic conditions of the research. The zone of the research is characterized by semi-arid natural-climatic conditions. The average statistical value of the norm (the period of 1970–2020) of the air temperature in the growing season equals 18.0 °C (Fig. 2, *a* (see p. 210)), the standard deviation is 4.9 °C, the level of variance is 27.3%, the sum of average month temperatures are 89.9 °C. In particular, the average value of the air temperature in the growing season in a dry year (2020) made 19.0 °C, the standard deviation was 6.3 °C, the level of variance was 33.3%, the sum of average month temperatures equaled 94.8 °C. In a medium wet year (2019) the average value of the air temperature in the growing season was 20.4 °C, the standard deviation was 5.5 °C, the level of variance equaled 27.0%, the sum of average month temperatures were 102.0 °C. In a wet year (2021) the average value of the air temperature in the growing season was 18.4 °C, the standard deviation was 6.6 °C, the level of variance was 35.8%, the sum of average month temperatures equaled 92.2 °C.

An increased level of variance in dry and wet years indicate manifestations of unstable changes in the temperature regime of the growing season, in dry years there were seasonal sharp increases in the air temperature, in wet years there was a drastic decline in the air temperature. Sharp changes in the temperature regime in the Steppe zone in the growing season of sunflower crops are asynchronous with regard to the amount of precipitation. In particular, manifestations of the high temperature regime intensify the process of transpiration and evaporation, increase expenditures of groundwater in the growing season.



a *b*

Figure 2. Climatic conditions for the growing season of sunflower growing in 2019–2021:
a – average monthly air temperature (°C); *b* – amount of precipitation (mm)

There has been an increase in the frequency of abnormal manifestations of heavy rainfalls over the past 10–15 years. In July, 2020 (Fig. 2, *b*) there was an extreme increase in the vegetation index during the period of sunflower flowering (BBCH 61–69), but heavy rainfalls did not have positive energy and a long-term effect on the formation of sunflower hybrid productivity. In particular, in a dry year (2020) a high level of the standard deviation (84.1 mm) and a high level of variance of seasonal changes in precipitation (139.7%) were registered that confirms their abnormal manifestations in the growing season.

It is necessary to highlight that the average monthly value of the norm of precipitation in the growing season for 50 years (1970–2020) was 43.6 mm, the standard deviation was 12.6 mm, the level of variance equaled 28.9%. The year of 2019 was close to the typical climatic conditions (the norm): the average monthly value of precipitation in the growing season was 47.0 mm, the standard deviation was 13.3 mm, the level of variance equaled 28.3%. The year of 2021, a typical wet year for the Steppe zone, was characterized by the average monthly value of precipitation of 72.8 mm, the standard deviation of 32.4 mm and an increased level of variance – 44.5%.

Well-developed sunflower crops consume from 500 mm to 600 mm of water in the growing season, and the minimum water demand of plants is met with 300–400 mm of precipitation. In the growing season of 2019 the total amount of precipitation equaled 235 mm (Fig. 2, *b*), in 2020 – 295 mm (in July there was unusually abnormal amount – 70.5% of the amount in the growing season, unproductive heavy rainfalls), in 2021 – 364 mm. The value of the norm of the total precipitation in the research territory was 218 mm.

Under arid conditions of the Steppe zone of Ukraine, the level of moisture content of soil is a limiting factor of the formation of agrocenoses productivity. It was established that 60–70% of the total water uptake by sunflower crops in the growing season was provided with precipitation, 30–40% – with moisture content in the soil. It was found that pre-sowing moisture content in a meter layer of soil in the research fields in a dry year (2020) was 41 mm, in a medium-wet year (2019) – 69 mm, in a wet year (2021) – 89 mm. In particular, the second half of the growing season in 2019 was characterized by a 23.9% deficiency in regard to the norm of atmospheric moisture and an increase in the air temperature by 11.5%, that caused stress in plants and, consequently, a drop in productivity. In a dry year (2020) sunflower hybrids were under permanent influence of climatic stress, determined by a significant deficiency of soil and atmospheric moisture with extreme unproductive heavy rainfalls and a high air temperature in July. In particular, in a wet year (2021) there were no signs of stressful weather conditions and there was productive precipitation over the period of budding-flowering (BBCH 51–69), which is a necessary crucial phenological stage of plant development for the formation of sunflower hybrid yields. Therefore, under conditions of extreme agriculture of the Steppe zone, agro-technological measures are aimed at retaining moisture.

Examination of the state of sunflower hybrid crops. Sunflower yield depends on genetic properties of a hybrid, its phyto-potential, soil and natural-climatic conditions of the area, elements of varietal agro-technology (Flagella et al., 2002; Ibrahim, 2012). A change in activeness of plant photosynthetic processes and production of chlorophyll content at a certain macro-stage and phenological stage is an indicator of plant development. Research on changes in photosynthetic activeness of sunflower hybrids was carried out on the basis of analysis of the values of NDVI, which is a popular index for forecasting agrocenoses productivity.

The index value of NDVI in the research fields, in 2019, 2020 and 2021, was calculated on the basis of the data of satellite images of the space vehicle Sentinel 2. Using the images, we identified the state of plant herbage, absorbing electromagnetic waves in a visible red band and reflects them in a near infra-red band. In particular, (the central length of the wave of Sentinel 2 is 665 nm) maximum absorption of solar radiation by chlorophyll falls on a red spectrum zone, and maximum reflection of energy by a leaf cell structure falls on a near infrared zone (the central length of the wave of Sentinel 2 is 842 nm).

A medium-met year (2019). As a result of decoding the series of satellite images in a medium-wet year (2019), at the beginning of the growing season (May, 5, 12 days after the sowing date), we identified simultaneous germination (Fig. 3, see p. 213) in the sunflower hybrid crops with the average index value of NDVI – 0.26 ± 0.03 and an insignificant level of spatial variance – 8.1%.

After foliar treatment of sunflower hybrids, there was heterogeneous reaction of the plants to multifunctional growth-regulators, that was registered on the satellite image on May, 30 (37 days after the sowing date). It is necessary to emphasize a positive reaction and intensification of the development of the crop hybrid Oplot, the value of NDVI ranged from 0.54 to 0.77, the hybrid Hector with the values of NDVI within 0.54–0.80 and the hybrid DSL403 with the values of NDVI – 0.51–0.78. There was a weak reaction to growth-regulators in the hybrid P64HE133 with the value of NDVI – 0.41–0.67 and the hybrid 8KH477KL with the value of NDVI – 0.43–0.62. At the end of the phenological stage “capitulum formation”, on June, 14 (52 days after the sowing date) and the beginning of the stage “flowering”, on June, 19 (57 days after the sowing date), we registered a good (0.55–0.7) and very good state of the vegetation of all the sunflower hybrids (>0.7). In this period the average value of NDVI equaled 0.72 ± 0.06, the level of spatial heterogeneity was 8.2%. Homogeneity of plant vegetation is an evidence of a complex effect of productive precipitation and multifunctional plant growth-regulators.

The second half of the growing season of the sunflower hybrids in 2019 includes the second half of the flowering stage (BBCH 67–69) and the macro-stages "fruiting" (BBCH 71–79), "fruit and seed

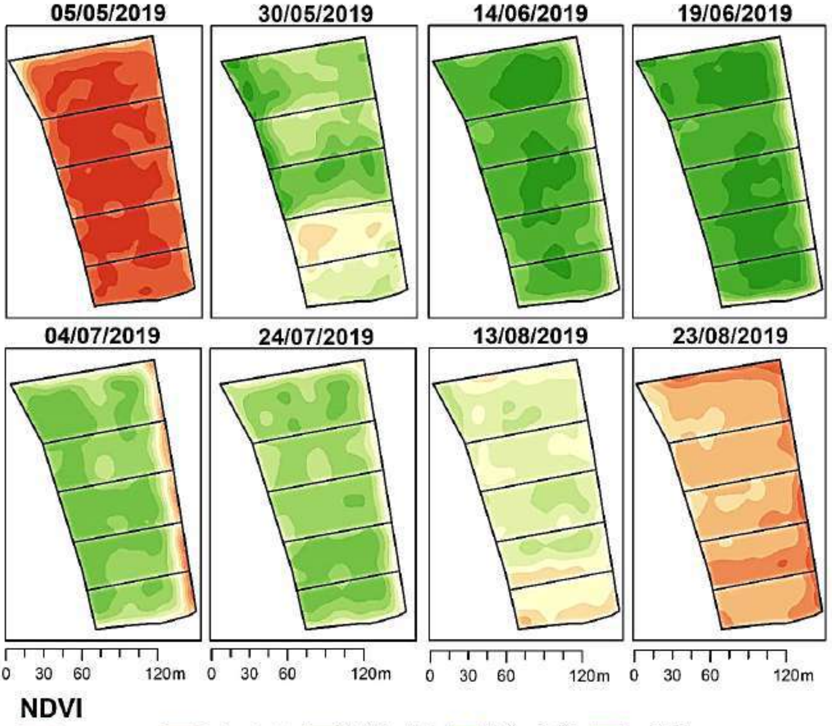


Figure 3. Seasonal distribution of NDVI of the sunflower hybrids in the research field (2019)

maturation" (BBCH 80–89) and "dying" (BBCH 92–99), which are components of the phenological stage of maturation (BBCH 71–99). It is necessary to highlight that the second half of the growing season was characterized by stressful conditions, determined by water deficiency and an increased air temperature. It caused a sharp deterioration in photosynthetic processes and shorter duration of the macro-stage "fruiting". On July, 4 (72 days after the sowing date) we registered a medium value of NDVI – 0.63 ± 0.09 with visible signs of heterogeneity of the formation of the sunflower hybrid productivity, the level of spatial variance being 14.1%.

In the course of the macro-stage "fruit and seed maturation", on July, 24 and August, 13, we registered fast seed maturation of the hybrids P64HE133 and 8KH477KL. At the macro-stage "dying" from the period of full maturity (the seed moisture content is about 10%, BBCH 92) to harvesting (August, 23), the average value of NDVI equaled 0.37, on August, 26 – 0.30.

A dry year (2020). In 2020 there were extremely dry conditions for growing sunflower hybrids, that caused a reduction in the growing season and dates of certain phenological stages of plants. In particular, the beginning of the growing season in 2020 was characterized by a low level of soil moisture content and a small amount of precipitation. It determined poor germination and a critically low level of photosynthetic processes at the beginning of the phenological stage of capitulum formation (Fig. 4, see p. 215).

After treating the crops during the period of the formation of 6–8 true leaves, there were slow reactions of all the hybrids to multifunctional growth-regulators, that was determined by stressful climatic conditions. The data of the decoded satellite image created on May, 19 (21 days after the sowing date) allowed calculating a low level of the value of NDVI – 0.23 ± 0.02 with an insignificant level of variability – 8.2%.

Deficiency of precipitation caused further stunted plant growth that was confirmed by the results of the decoded satellite image created on June, 8 (41 days after the sowing date), the value of NDVI equaled 0.36 ± 0.04 with a significant level of variance – 10.3%. June of 2020 was characterized by heavy rainfalls enhancing the effect of growth-regulators on photosynthetic processes in the sunflower hybrids. At the beginning of the flowering stage, on June, 23 (56 days after the sowing date), the value of NDVI equaled 0.70 ± 0.03 with an insignificant level of variance – 4.9%.

The end of the flowering stage, July, 3 (56 days after the sowing date), was also characterized by high values of NDVI – 0.69 ± 0.03 with the level of variance – 9.8%. Deficiency of atmospheric and soil moisture in the second half of the plant growth caused a sharp

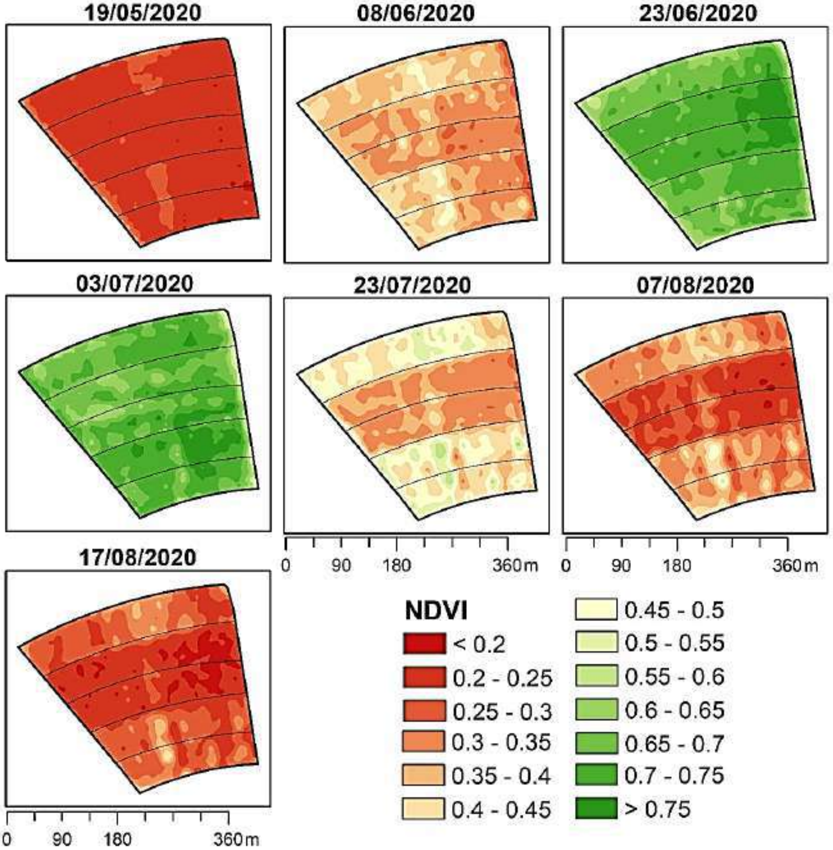


Figure 4. Seasonal distribution of NDVI of the sunflower hybrids in the research field (2020)

decline in photosynthetic activeness of the sunflower hybrids and shorter duration of the macro-stage “fruiting” (BBCH 71–79), stimulated faster “fruit and seed maturation” (BBCH 80–89) and “dying” (BBCH 92–99), on July, 23 (86 days after the sowing date) the value of NDVI equaled 0.41 ± 0.04 with the level of variance – 9.8%. On August, 7 (101 days after the sowing date) the value of NDVI equaled 0.30 ± 0.04 with a high level of variance – 12.2%.

At the plant macro-stage “dying”, on August, 17–18 (112 days after the sowing date), the value of NDVI was 0.25 ± 0.03 with a high level of spatial variance – 11.6%. A high level of spatial variance is determined by considerable spatial heterogeneity of plants because of stress caused by climatic conditions. It was established that the sunflower hybrids Hector and DSL403 matured faster in dry periods. Deficiency of moisture caused deterioration in photosynthetic processes, a significant decline in chlorophyll content in the plants, a shorter duration of important phenological stages and the growing season of the sunflower hybrids on the whole.

A wet year (2021). The beginning of the growing season in 2021 was characterized by favorable climatic conditions in the pre-sowing period, that ensured a high level of moisture content in the soil in the sowing period. It determined high energy and uniform emergence of seedlings registered on May, 14 (5 days after the sowing date), the index value of NDVI was 0.25 ± 0.03, the level of spatial variance equaled 6.2% (Fig. 5, see p. 217).

After the plant treatment, on June, 8 (21 days after the sowing date), there was high heterogeneity of the hybrid reaction to multifunctional growth-regulators, that was determined by redistribution of moisture in the field and the hybrid plasticity in response to the climatic conditions of the Steppe zone. The value of NDVI equaled 0.42 ± 0.04 with a high level of spatial variance – 14.0%.

High photosynthetic capacity of the hybrid Oplot was registered in this period, the value of NDVI reached the level of 0.56. A comparatively low level of photosynthesis was registered in the hybrids DSL403 (NDVI – 0.39) and P64HE133 (NDVI – 0.40).

At the phenological flowering stage of the sunflower crops, all the hybrids were characterized by a high level of photosynthetic process, on June, 23 (45 days after the sowing date) the value of NDVI equaled 0.75 ± 0.06 with the level of spatial variance – 8.5%. Systematic productive precipitation and high moisture content

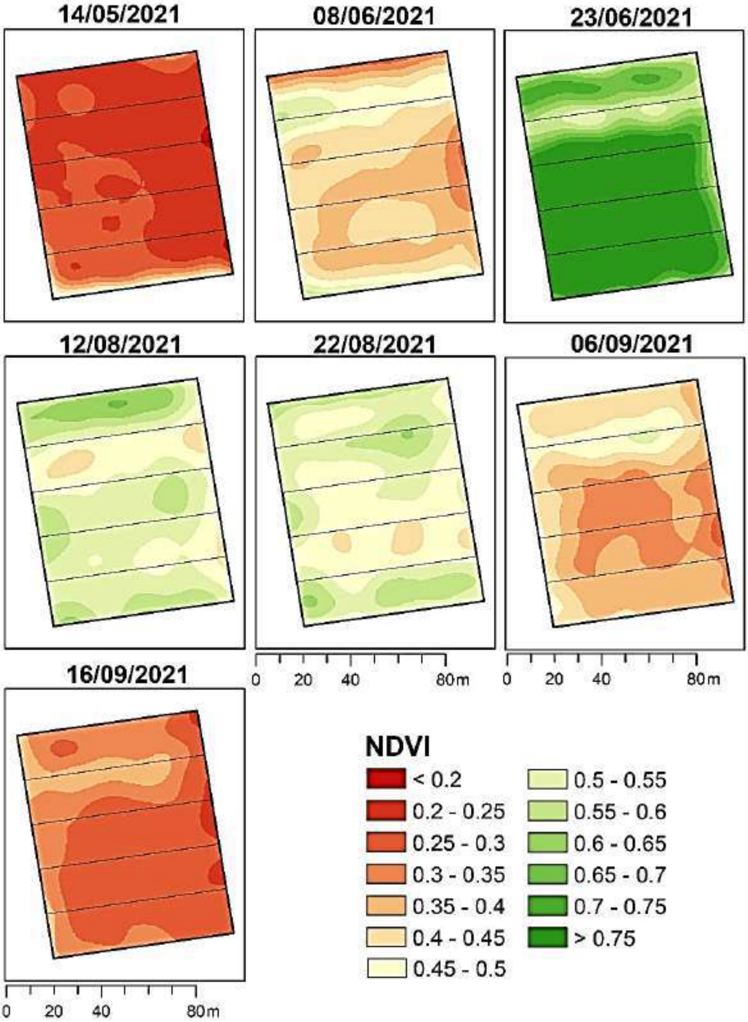


Figure 5. Seasonal distribution of NDVI of the sunflower hybrids in the research field (2021)

in the soil in the first half of the growing season determined a longer phenological stage of flowering that contributed to an increase in the plant productivity. In 2021 the flowering stage lasted 33 days that was 2.3 times longer than in the previous years of 2019 and 2020. The maximum value of NDVI in the flowering period – 0.89–0.93. A high level of NDVI was registered at the phenological stage of “fruiting” – 0.74 (76 days after the sowing date) and the macro-stage “fruit and seed maturation” – 0.54 (95 days after the sowing date).

A high level of moisture content, application of complex multifunctional growth-regulators, longer duration of the flowering staged created favorable conditions for fruit formation and sunflower seed maturation. At the end of the macro-stage “fruit and seed maturation”, on September, 6 (119 days after the sowing date), the value of NDVI equaled 0.39, at the macro-stage “dying” and at harvest time, on September, 12 the value of NDVI equaled 0.32. Spatial variance in the plant growing season was determined by spatial differentiation of soil moisture, heterogeneity of the sunflower hybrid reaction to growth-regulators and different levels of the hybrid plasticity in response to the weather conditions of the Steppe zone.

Analysis of the sunflower hybrid productivity. The results of the experimental field research and analysis of the change in the state of sunflower hybrid crops under different climatic conditions allowed establishing effectiveness of application of multifunctional growth-regulators for improving the plant growing conditions aimed at increasing the sunflower hybrid productivity (Table 1, see p. 219).

A positive reaction to application of growth-regulators and plasticity in response to extreme weather conditions were observed in the sunflower hybrids Oplot and P64HE133, that was confirmed by an increase in their productivity. The productivity of these hybrids was higher in the dry year – by 0.10–0.34 t/ha, in the medium-wet year – by 0.38–0.86 t/ha, in the wet year – by 0.26–0.87 t/ha. Low plasticity and a decline in productivity were observed in the hybrid Hector. Medium indexes of productivity were characteristic of the hybrids DSL 403 and 8KH477KL, in the dry year their productivity was lower than in the medium-wet year by 18.1–34.5%, and there was an increase in their productivity by 0.3–30.4% in the wet year.

Table 1. Sunflower productivity depending on foliar treatment with growth-regulators in the years of the research, t/ha

Hybrids (Factor A)	**Preparation (Factor B)**	**Years**			**Average for 3 years**
		2019	**2020**	**2021**	
Oplot	Without preparations (control)	2.82	1.98	2.88	2.56
	Architect™	3.07	2.01	3.12	2.73
	Helafit Combi	3.10	2.04	3.11	2.75
Hector	Without preparations (control)	1.92	1.54	2.04	1.83
	Architect™	2.14	1.68	2.23	2.02
	Helafit Combi	2.10	1.72	2.22	2.01
DSL 403	Without preparations (control)	2.44	1.83	2.54	2.27
	Architect™	2.55	1.88	2.86	2.43
	Helafit Combi	2,60	1.93	2.90	2.48
P64HE133	Without preparations (control)	2.71	1.90	2.92	2.51
	Architect™	2.88	1.95	3.05	2.63
	Helafit Combi	2.89	2.02	3.10	2.67
8KH477KL	Without preparations (control)	2.22	1.68	2.41	2.10
	Architect™	2.37	1.71	2.96	2.35
	Helafit Combi	2.37	1.74	3.09	2.40
LSD05, t/ha	Factor A	0.09	0.07	0.09	—
	Factor B	0.12	0.11	0.10	—
	Interaction of Factors A and B	0.25	0.21	0.24	—

It was proved that foliar treatment with combined growth-regulators had a positive effect on an increase in the sunflower hybrid productivity. The highest average productivity in 2019–2021 was characteristic of the sunflower hybrid Oplot – 2.75 t/ha (treatment with the biological growth-regulator Helafit Combi).

Analysis of the reaction of different sunflower hybrids to multifunctional growth-regulators allowed finding (Fig. 6) that the chemical preparation Architect™, in comparison with the control, led to an increase in productivity in the dry year – from 1.5% to 9.1%, in the medium-dry year – from 4.5 to 11.5%, in the wet year – from 4.5% to 22.8%. In particular, application of the biological preparation Helafit Combi led to an increase in the sunflower hybrid productivity in the dry year – from 3.0 to 11.7%, in the medium-wet year – from 6.6% to 9.9%, in the wet year – from 6.2% to 28.2%.

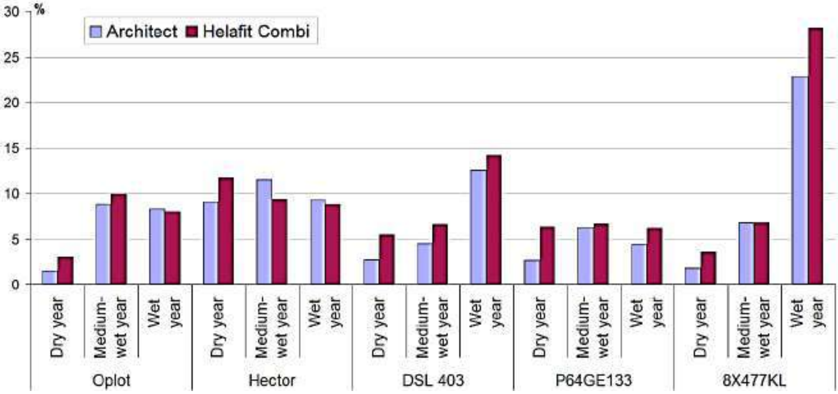


Figure 6. Effect of multifunctional growth-regulators on an increase in the productivity (%) of sunflower hybrids under conditions of the Steppe zone

The research allowed identifying the advantage of the effect of the biological preparation Helafit Combi over the chemical preparation Architect™ by 1.2 times. High sensitivity to the preparations in the dry and medium-wet years was registered in the hybrid Hector, an increase in its productivity being 9.1–11.7%. In the wet year, application of the preparations led to a high increase in the productivity of the hybrid DSL403 from 12.6 to 14.2%, and that of the hybrid 8KH477KL from 22.8 to 28.2%. We established dependence of the reaction of the sunflower hybrids to multifunctional growth-regulators on the plasticity of these hybrids in response to the natural-climatic conditions of the Steppe zone.

There was a weak reaction to application of growth-regulators in the sunflower hybrids Oplot and P64HE133 which have a high level of plasticity in response to the natural-climatic conditions of the Steppe zone. Higher values of an increase in productivity in 80% of the variants were registered when the biological growth-regulator Helafit Combi was applied. Application of the biological preparation Helafit Combi exceeded the level of agrocenoses productivity by 1.1–5.4% in comparison with the chemical preparation Architect™.

Forecasting sunflower hybrid productivity. Sunflower plants have a well-developed root system and an ability to consume water from the soil layer of 2–4 meters deep in dry years, but the crop has special requirements for water supply. At different phenological stages sunflower plants consume moisture unevenly, the most active water uptake occurs at the stages of intensive growth, flowering and seed filling. From seedling emergence (BBCH 09) to capitulum formation (BBCH 15) sunflower plants consume about 20% of moisture in the growing season; at the phenological stages of capitulum formation (BBCH 16–59) and flowering (BBCH 61–69) consumption of total moisture in the growing season is 60%, this period is crucial in the formation of crop yields; 20% of moisture in the growing season is consumed by plants at the stage of fruiting and at the beginning of maturation (BBCH 71–80). Autumn-winter supply of soil moisture is also very important for sunflower plants. It was established that water uptake by sunflower hybrid plants for the formation of a unit of the crop yield (t/ha) in the years of the research was: in a dry year – 927 ± 80 m^3/ha, in a medium-wet year – 1,106 ± 163 m^3/ha, in a wet year – 1,540 ± 232 m^3/ha. In particular, when there is moisture deficit at the beginning of plant growth, leaf surface area gets smaller and there are less flowers in the capitulum that causes a decline in the crop yields. When there is moisture deficit in the second half of the growing season, leaves get older fast, that results in lower oil content in the seeds.

Sunflower plants absorb 60% of nitrogen, 80% of phosphorus and 90% of potassium of the total nutrient depletion in the growing season from sprouting to the beginning of flowering (BBCH 09–61).

The capitulum size and the number of seeds in it depends on the plant growth from seedling emergence (BBCH 09) to capitulum formation (BBCH 15). In this period the formation of capitulum buds occurs, flower buds emerge, plants actively assimilate nitrogen, potassium and intensively – phosphorus. The formation of capitulum buds in sunflower hybrids occurs at the stage BBCH 16–19. Therefore, this stage (BBCH 14–18) is appropriate for foliar and root feeding. By the end of the period the stem growth ceases, but the root system continues to grow, reaching the deepest horizons, especially when there is no moisture in the upper horizon. At this period the largest share of moisture and nutrients from soil is absorbed, therefore, plant feeding before the beginning and at the beginning of this stage is effective, especially chelate foliar feeding.

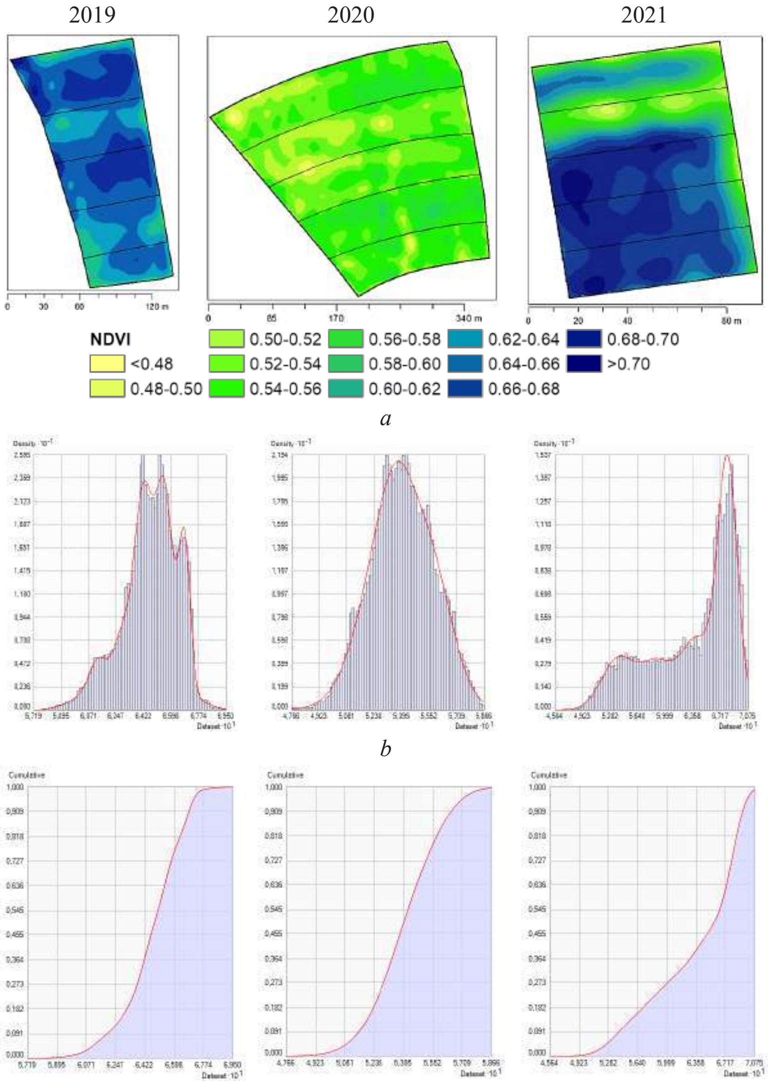
From the beginning of flowering to the beginning of maturation (BBCH 63–80) plants absorb about 40% of nitrogen, 20% of phosphorous and 10% of potassium from the soil. This period is characterized by moderate assimilation of nitrogen, phosphorous and intensive assimilation of potassium. The macro-stage of fruiting (BBCH 71–79) is crucial for the number of seeds per capitulum, their size, weight and oil content. At this stage sunflower plants are especially sensitive to the level of moisture in soil. After the stage of seed filling completes, the macro-stage of seed maturation (BBCH 80–89) and physiological maturity starts, biological processes cease and moisture evaporation begins. In particular, at the stage of maturation, sunflower seeds contain 60% of nitrogen, 70% of phosphorus and 10% of potassium. The substantial amount of nutrients remains in leaves, stems and capitula, and after harvesting it returns to soil. About 55 ± 5.0 kg of nitrogen, 22 ± 3.0 kg of phosphorus and 110 ± 10.0 kg of potassium are spent on the formation of 1 ton of sunflower seeds and herbage. About 90% of sunflower nutritional needs are provided by the root system, and 10% – by leaf nutrition. Leaves absorb solar energy, carbon, oxygen, nitrogen, sulfur and other necessary nutrients.

Determination of a NDVI in the main periods of moisture supply and mineral nutrition of sunflower hybrids in the growing season allowed creating a general cartogram of spatial distribution of the values of a vegetation index in 2019, 2020 and 2021. Generalized cartograms of the values of a $\mathrm{NDVI}_{\mathrm{year}}$ are the sum of raster surfaces of differentiation of the values of a NDVI at the main stages of plant growth. In particular, the first raster surface identifies the value of a NDVI at the beginning of the formation of capitulum buds at the macro-stage BBCH 16–19, the second raster surface contains the values of a NDVI of the characteristics of the macro-stages BBCH 61–67, the third raster surface contains distribution of the values of a NDVI of the macro-stage BBCH 79–80. The weighing coefficient of a cumulative impact of the values of moisture uptake and absorption of mineral nutrients on the formation of the crop yields was assigned to a corresponding raster of a NDVI. Thus, the weighing coefficient 0.2 was assigned to the values of the raster surface of a $\mathrm{NDVI}_{\mathrm{BBCH\ 16–19}}$, the weighing coefficient 0.6 was assigned to the values of a $\mathrm{NDVI}_{\mathrm{BBCH\ 61–67}}$, the weighing coefficient 0.2 was assigned to the values of the raster surface of a $\mathrm{NDVI}_{\mathrm{BBCH\ 79–80}}$.

The generalized cartogram of the values of a NDVI is created by the formula:

$$NDVI_{\mathrm{year}} = 0.2NDVI_{BBCH\ 16-19} + 0.6NDVI_{BBCH\ 61-67} + 0.2NDVI_{BBCH\ 79-80}. \quad (2)$$

Using a raster calculator, we calculated spatial differentiation of the values of a $\mathrm{NDVI}_{\mathrm{year}}$, correlating functionally with spatial variance of sunflower hybrid productivity (Fig. 7, see p. 224). It was established that in the medium-wet year of 2019 the value of a $\mathrm{NDVI}_{\mathrm{year}}$ ranged from 0.57 to 0.69, in the dry year of 2020 it equaled 0.48–0.59, in the wet year of 2021 it was 0.49–0.71. It was established that the values of a vegetation index reflect photosynthetic processes and production of chlorophyll content, which depend on the conditions of moisture content and the quantity of mineral nutrients, but do not identify genetic features and hybrid plasticity in response to soil-climatic conditions of physical-geographical zones. Therefore, in order to clarify the correspondence of the values of a $\mathrm{NDVI}_{\mathrm{year}}$ to the productivity of certain hybrids, we normalized the values of a $\mathrm{NDVI}_{\mathrm{year}}$ through mathematical relation between raster values of the vegetation index and its average



a

b

c

Figure 7. Spatial differentiation of the generalized values of a NDVI of sunflower hybrids in 2019–2021:
a – cartograms; *b* – histogram; *c* – cumulative curve

value of a corresponding year. Calculations allowed creating rater surfaces in which the value “1” corresponded to the average value of a $\mathrm{NDVI}_{\mathrm{year}}$ of a certain year. In its turn, the average value of a $\mathrm{NDVI}_{\mathrm{year}}$ of a certain plot corresponded to the average value of productivity of a corresponding sunflower hybrid.

Further we calculated the average productivity of each sunflower hybrid which had the following values: Oplot in 2019 – 3.0 t/ha, in 2020 – 2.01 t/ha, in 2021 – 3.04 t/ha; Hector in 2019 – 2.05 t/ha, in 2020 – 1.65 t/ha, in 2021 – 2.16 t/ha; DSL 403 in 2019 – 2.53 t/ha, in 2020 – 1.88 t/ha, in 2021 – 2.77 t/ha; P64GE133 in 2019 – 2.83 t/ha, in 2020 – 1.96 t/ha, in 2021 – 3.02 t/ha; 8X477KL in 2019 – 2.32 t/ha, in 2020 – 1.71 t/ha, 2021 – 2.82 t/ha.

These data were used to create cartograms of spatial differentiation of sunflower hybrid productivity (Fig. 8, see p. 226) in relation to distribution of the normalized values of a $\mathrm{NDVI}_{\mathrm{year}}$ by the formula:

$$CY_{year} = \frac{NDVIi_{year}}{Aver(NDVIi_{year})} \times Aver(CY_i)\,, \tag{3}$$

where $NDVIi_{year}$ – the value of a vegetation index of the research plot of a certain crop variety or hybrid; $Aver(NDVIi_{year})$ – the average value of a vegetation index of the research plot of a certain crop variety or hybrid; $Aver(CY_i)$ – the average value of the productivity of a certain crop variety or hybrid on the research plot.

The cartograms of the crop yields allow establishing spatio-temporal heterogeneity of the productivity of certain sunflower hybrids depending on the climatic conditions of 2019, 2020 and 2021. In the medium-wet year the productivity of sunflower yields ranged from 1.86 to 3.18 t/ha, there was significant differentiation of sunflower hybrid productivity (Fig. 9, *a* (see p. 227) – 2019), the histogram shows their distinct boundaries (Fig. 9, *b* (see p. 227) – 2019). We registered the minimum values of productivity in the hybrids Hector – 1.86–2.15 t/ha and 8X477KL – 2.10–2.42 t/ha, the medium level of productivity of DSL 403 – 2.44–2.60 t/ha, the maximum value of productivity was in the hybrids Oplot – 2.70–3.18 t/ha and P64GE133 – 2.65–2.92 t/ha.

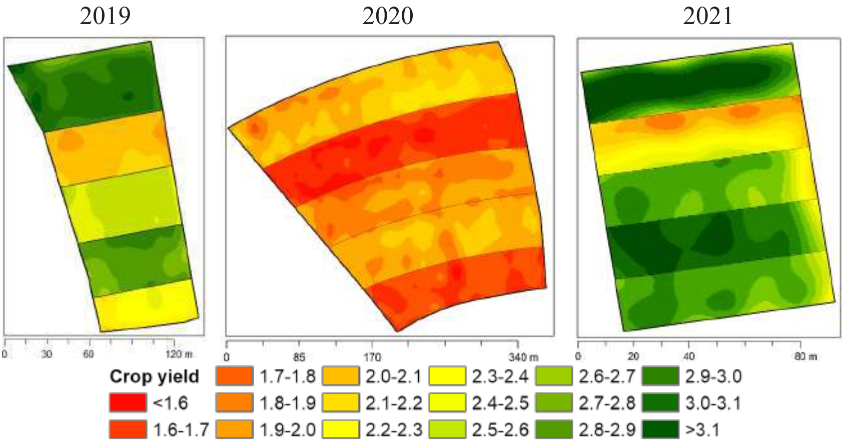
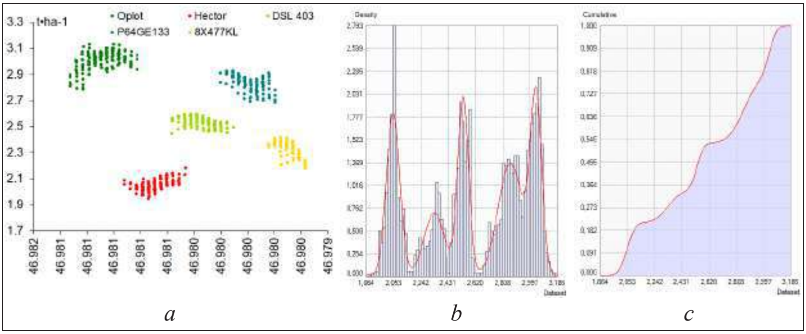


Figure 8. Cartograms of distribution of the crop yields of sunflower hybrids in 2019–2021

In the dry year (Fig. 9 (see p. 227) – 2020) the histogram differentiates two samples, the first one characterizes distribution of the minimum values of productivity of the hybrids Hector – 1.53–1.76 t/ha and 8XH477KL – 1.58–1.81 t/ha, and the second one combines the values of the medium and the maximum productivity of the hybrids DSL 403 – 1.75–2.00 t/ha, P64GE133 – 1.80–2.06 t/ha and Oplot – 1.85–2.16 t/ha. In the wet year (Fig. 9 (see p. 227) – 2021) the minimum value of productivity was identified in the hybrid Hector – 1.82–2.56 t/ha, the medium level of productivity was registered in the hybrids DSL 403 – 2.65–2.93 t/ha and 8X477KL – 2.50–2.98 t/ha, the maximum level of productivity was registered in the hybrids Oplot – 2.60–3.37 t/ha and P64GE133 – 2.80–3.17 t/ha.

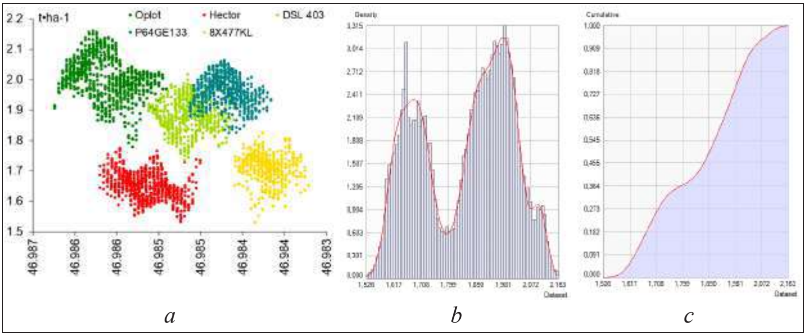
It was established that each sunflower hybrid is characterized by individual genetic features of plant plasticity in response to the soil-climatic conditions of the Steppe which determine the crop yields. Therefore, a model of the function of forecasting crop yields was developed for each hybrid (Table 2, see p. 228–229).

The medium-wet year of 2019



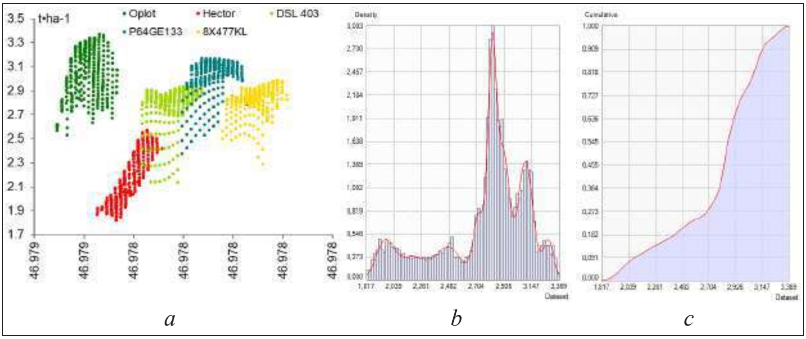
a *b* *c*

The dry year of 2020



a *b* *c*

The wet year of 2021



a *b* *c*

Figure 9. Spatial differentiation of sunflower hybrid productivity in 2019–2021:
a – graph of spatial differentiation; *b* – histogram; *c* – cumulative curve

Functions with a high level of approximation (r^2) describe spatio-temporal process of the yield formation of certain sunflower hybrids in relation to the level of water supply in a year. The function models were created on the basis of three raster periods of water uptake and

Table 2. Functions of forecasting and graphs of normal distribution of sunflower hybrid productivity on the basis of the data of 2019–2021

Oplot
2019 (the medium-wet year) $Y = 0.914NDVI_1 + 2.739NDVI_2 + 0.923NDVI_3, \quad r^2 = 0.996$ 2020 (the dry year) $Y = 0.745NDVI_1 + 2.235NDVI_2 + 0.745NDVI_3, \quad r^2 = 0.999$ 2021 (the wet year) $Y = 1.038NDVI_1 + 3.114NDVI_2 + 1.038NDVI_3, \quad r^2 = 0.999$
Hector
2019 (the medium-wet year) $Y = 0.628NDVI_1 + 1.807NDVI_2 + 0.731NDVI_3, \quad r^2 = 0.988$ 2020 (the dry year) $Y = 0.585NDVI_1 + 1.841NDVI_2 + 0.624NDVI_3, \quad r^2 = 0.972$ 2021 (the wet year) $Y = 0.619NDVI_1 + 2.166NDVI_2 + 0.795NDVI_3, \quad r^2 = 0.996$
DSL 403
2019 (the medium-wet year) $Y = 0.758NDVI_1 + 2.220NDVI_2 + 0.798NDVI_3, \quad r^2 = 0.989$ 2020 (the dry year) $Y = 0.701NDVI_1 + 2.107NDVI_2 + 0.703NDVI_3, \quad r^2 = 0.999$ 2021 (the wet year) $Y = 0.839NDVI_1 + 2.464NDVI_2 + 0.833NDVI_3, \quad r^2 = 0.987$
P64GE133
2019 (the medium wet year) $Y = 0.857NDVI_1 + 2.644NDVI_2 + 0.974NDVI_3, \quad r^2 = 0.999$ 2020 (the dry year) $Y = 0.704NDVI_1 + 2.111NDVI_2 + 0.704NDVI_3, \quad r^2 = 0.999$ 2021 (the wet year) $Y = 0.878NDVI_1 + 2.706NDVI_2 + 0.917NDVI_3, \quad r^2 = 0.980$

End of Table 2

8X477KL
2019 (the medium-wet year)
$Y = 0.629 NDVI_1 + 1.887 NDVI_2 + 0.629 NDVI_3, \quad r^2 = 0.999$
2020 (the dry year)
$Y = 0.629 NDVI_1 + 1.887 NDVI_2 + 0.629 NDVI_3, \quad r^2 = 0.999$
2021 (the wet year)
$Y = 0.845 NDVI_1 + 2.535 NDVI_2 + 0.845 NDVI_3, \quad r^2 = 0.999$

mineral nutrition of plants. The value of a $NDVI_1$ contains the average value or raster surface of spatial distribution of a vegetation index of sunflower hybrids at the macro-stage of the formation of capitulum buds BBCH 16–19, the value of a $NDVI_2$ contains the average value or raster surface of spatial distribution of a vegetation index of sunflower hybrids at the macro-stage of flowering BBCH 61–67, the value of a $NDVI_3$ contains the average value or raster surface of spatial distribution of a vegetation index of sunflower hybrids at the end of the macro-stage of fruiting and the beginning of seed maturation (BBCH 79–80).

Using the data of 2019, 2020 and 2021, taking the hybrid Oplot as an example, we created a versatile model of the function of forecasting crop yields depending on a vegetation index:

$$Y = 1.957 NDVI_1 + 0.493 NDVI_2 + 3.310 NDVI_3, \quad r^2 = 0.952 . \qquad (4)$$

According to the level of approximation (r^2), it was established that the function appropriately describes the general tendency of the yield formation of sunflower hybrids depending on a vegetation index, but it has a low level of reliability in certain years different in water supply that reduces practical value of the function and confirms a high level of errors in calculations (Fig. 10, see p. 230).

Thus, in the conditions of the dry year (2020) the function was characterized by a low level of approximation r^2 – 0.309 in the description of the process of the yield formation, there was a high level of variance of errors in calculations of the entire sample, the value of errors reached 15–30%. In the medium-wet year (2019) the function was characterized by a medium level of approximation of the actual data: r^2 – 0.632, there were significant deviations in the description of the maximum values of the crop productivity, the level of error in the description of the actual equaled 10–20%. A high level of approximation r^2 – 0.835 was registered for 2021, in particular, a relatively insignificant variance between the actual and calculated values of sunflower hybrid productivity, the error of the function reached 10–12%. A low level of practical application of versatile models of the function of forecasting crop yields was registered for all the sunflower hybrids examined in the research.

Therefore, application of a system of function models (Table 2), developed for different conditions of water supply and crop feeding are recommended for situational forecasts of crop yields. These functions ensured the level of approximation of the actual data at the level of 97.2–99.9%, that confirms a high reliability of forecasting sunflower hybrid productivity.

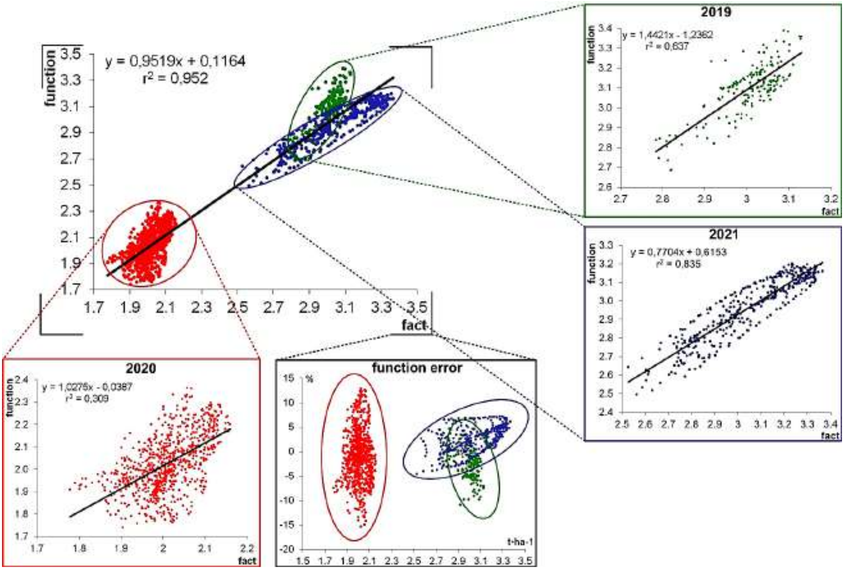


Figure 10. The level of approximation of a versatile model of the function of forecasting the productivity of the sunflower hybrid Oplot on the basis of the data of 2019–2021

CONCLUSIONS

The study proves that spatio-temporal research on differentiation of a vegetation index of agrocenoses allows evaluating efficiency of technologies for growing agricultural crops, establishing impacts of climate changes on a complex of agro-technological measures, examining plasticity of varieties and hybrids in response to certain soil-climatic conditions in order to make recommendations for improving them. It examines information of space images of the satellite Sentinel 2 for detailed analysis of seasonal changes in the values of a normalized difference vegetation index (NDVI) of sunflower hybrids.

The research determined the effectiveness of applying multifunctional growth-regulators. It identified a positive reaction to application of growth-regulators and plasticity of the hybrids Oplot and P64GE133 in response to the soil-climatic conditions of the Steppe zone, that was confirmed by an increase in their yields. The hybrid Hector showed low plasticity and a decline in its productivity. The hybrids DSL 403 and 8X477KL were characterized by medium indexes of their productivity. The study proves that foliar treatment with the combined growth-regulator Helafit Combi had a positive effect on an increase in sunflower hybrid productivity, the highest average crop yield in 2019–2021 was registered in the sunflower hybrid Oplot – 2.75 t/ha. Application of the biological preparation Helafit Combi exceeded the level of agrocenoses productivity in comparison with the chemical preparation Architect™ by 1.1–5.4%.

It was established that water uptake by sunflower hybrid plants for the formation of a unit of the crop yield (t/ha) in the years of the research equaled: the dry year – 927 ± 80 m^3/ha, the medium-wet-year – 1,106 ± 163 m^3/ha, the wet year – 1,540 ± 232 m^3/ha. Determination of a NDVI in the main periods of water supply during the growing season and feeding sunflower hybrids allowed creating a general cartogram of spatial distribution of the vegetation index values in 2019, 2020 and 2021. It was found that each sunflower hybrid is characterized by individual genetic features of plant plasticity in response to the soil-climatic conditions of the Steppe, determining the crop yields. Therefore, a model of the function of forecasting crop yields was created for each hybrid. The functions with a high level of approximation describe spatio-temporal processes of the yield formation of certain sunflower hybrids in relation to the level of water supply in a year. The function models were created on the basis of raster models of spatial distribution of the values of a NDVI at the most active stages of intensive growth, flowering and seed filling. A system of the function models developed for different conditions of water supply and crop mineral nutrition are recommended for situational forecasts of sunflower hybrid productivity. The suggested functions ensure the level of approximation of the actual data at the level of 97.2–99.9%, that confirms a high reliability of forecasting sunflower hybrid productivity.

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SPATIO-TEMPORAL RESEARCH ON THE EFFECT OF PRE-CROPS ON WINTER WHEAT GROWTH AND PRODUCTIVITY TO THE BBCH SCALE IN SOIL-CLIMATIC CONDITIONS OF THE STEPPE ZONE OF UKRAINE

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INTRODUCTION

Crop rotations are an important factor affecting physical-chemical properties of soils, intensity of crop growth and productivity, since they determine the course of technological processes (Theron et al., 2022; Liu et al., 2023). It is highly important to substantiate them in terms of ecological restoration in the Steppe zone of Ukraine (the zone of extreme agriculture), characterized by a low level of moisture supply and high temperatures (Lisetskii et al., 2016; Dudiak et al., 2019; Pichura et al., 2022). It was established that appropriate application of crop rotations improves micro-climate of farmlands (Schöning et al., 2023), contributes to accumulation of macro-elements (Breus et al., 2021, 2023; Xing et al., 2022) and moisture in soil (Domaratskiy et al., 2018; Wang et al., 2023), increases intensity of photosynthetic processes, production of chlorophyll content in leaves, enlarges the area of photosynthetic surface during the growing season (Jia et al., 2014), reduces the level of moisture evaporation from soil (Davis et al., 2017), facilitates moisture accumulation in plants and improves their stress-resistance under high temperatures (Nielsen et al., 2005; Domaratskiy et al., 2022).

Scientific studies prove optimality of a four-field rotation (varying from a three- to a five-field rotation) (Markovska, 2018). There should be a five- or an eight-field rotation in growing flax, lupine, sunflower, cabbage or melons. High yields are determined by crop rotations (Dogliotti et al., 2003), since a pre-crop assists in maintaining moisture regime that is especially important under conditions of the Steppe. It was found that plants absorb 550–700 m^3 of moisture for generation of 1 ton of dry corn yield for grain and sorghum, winter grain crops – 800–1,100 m^3, pea – 1,000–1,300 m^3, sunflower – 1,100–1,500 m^3 of moisture from soil during the growing season in the Steppe zone (Tsilyurik et al., 2020; Pichura et al., 2023). Black fallow is highly efficient in terms of moisture accumulation in soil, therefore, in the zone of extreme agriculture, in forecasted periods of low rainfall, it is recommended that black fallow be involved in crop rotation to improve productivity of agrocenoses (Wang et al., 2021; Gao et al., 2023).

It is recommended that crop rotations with 50% of grain crops, 25% of legumes (forage) and pulses, 25% of arable crops be used (Tsilyurik et al., 2018). Appropriate sequence of crops in crop rotations creates favorable conditions for plant nutrition (Domaratskiy et al., 2019; Guinet et al., 2020), and biological features of crops become a precondition of sustainable agriculture. Scientifically substantiated sequence of crops in crop rotations increases effectiveness of agro-technological practices, contributes to maintaining soil fertility, ensures high and stable yields (Jensen et al., 2020; Skok et al., 2023).

In the Steppe zone of Ukraine, there are three main directions in crop rotations: growing grain crops, oil-bearing crops, legumes and pulses (Sobko et al., 2021). Saturation of crop rotation with grain crops reaches 70–80%, including winter wheat, corn and other cereals (Zabrodotka et al., 2019). Therefore, it is necessary to include black fallow or sow legumes and pulses.

Violation of crop rotation rules causes weed growth, spread of pests and diseases, a reduction in effectiveness of chemical plant protection products (Kussul et al., 2022; Korkhova et al., 2023). For instance, winter wheat sown after winter wheat as a pre-crop is 1.4–1.7 times more susceptible to root rots, 1.5–2 times – to brown and yellow rust, 1.3–4 times – to snow mold (Zinchenko et al., 2001;

Bad’orna et al., 2009). Weed growth is 10 times higher. It is necessary to highlight that the productivity of winter wheat monocrop decreases 2–3 times in the fourth year, and the substantiated pre-crop ensures an increase in its productivity by 7.5–26.0% (Bugajov et al., 2021; Pyndus et al., 2022). In addition to an increase in productivity, the quality of agricultural products and environmental conditions improve.

The purpose of the study is to conduct spatio-temporal research on the effect of pre-crops on winter wheat growth and productivity in order to specify crop rotations, establish a pre-crop effectiveness and the level of agro-technological practices with further forecasting winter wheat productivity in soil-climatic conditions of the Steppe zone.

MATERIAL AND METHODS

The research territory and climatic conditions

The research on winter wheat growth and productivity in natural-climatic conditions of the Steppe zone depending on pre-crops was carried out during the crop growing season in 2021 (autumn) and 2022 (winter, spring, the beginning of summer). The experimental field is utilized by the farm “Svitlana” in the territory of Yelanets district, in Mykolaiv region, Ukraine. The total area of the experiments was 46.64 ha (Fig. 1, see p. 241), including: Plot 1 – pea as a pre-crop, the area of 14.20 ha; Plot 2 – a grain crop (spring barley) as a pre-crop, the area of 12.20 ha, Plot 3 – sunflower as a pre-crop, the area of 20.24 ha. The experiments were carried out without irrigation, using the winter wheat variety Driada 1 as an example. Location of the experimental field – N 47°63'05.2'' E 32°09'06.2''.

The research involved the actual values of near-surface air temperature (T, °C), total precipitation (P, mm) during the growing season in autumn 2021 and in winter, spring, the beginning of summer 2022 (Mykolaiv meteorological station).

Soil-morphometric characteristic of the experimental field

The experimental field is located in loess soils, medium- and slightly-eroded common black soils with low humus content. Humus

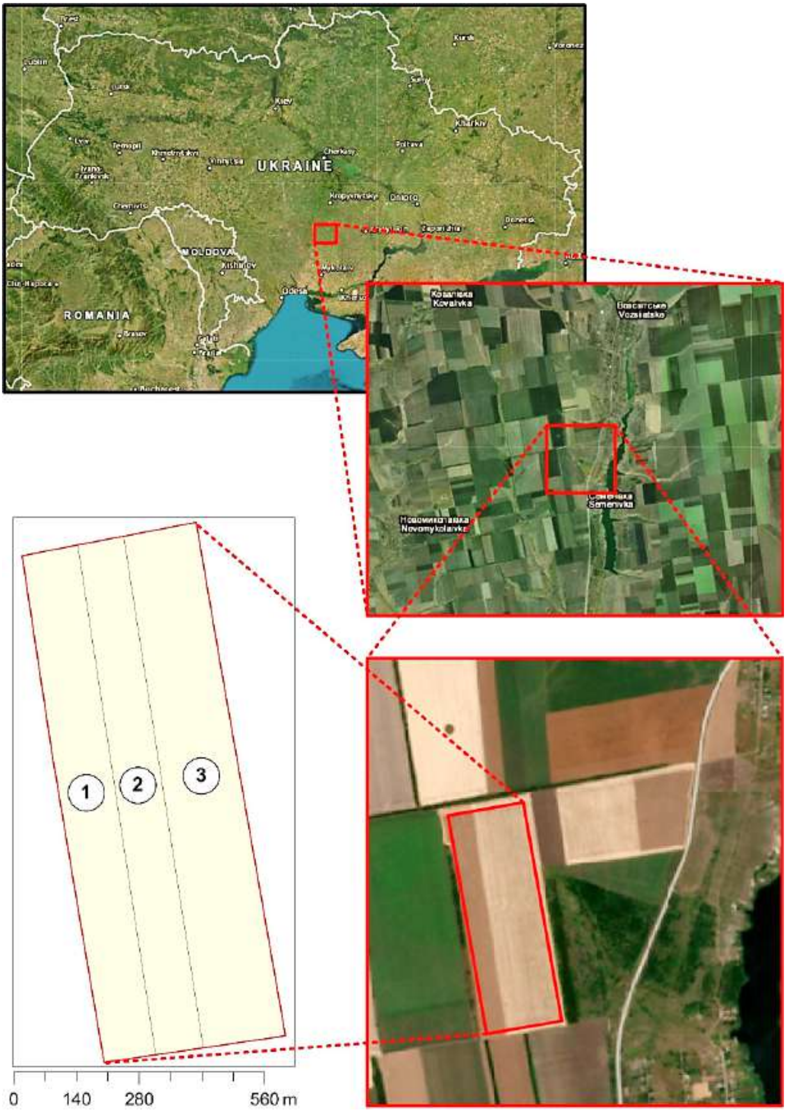
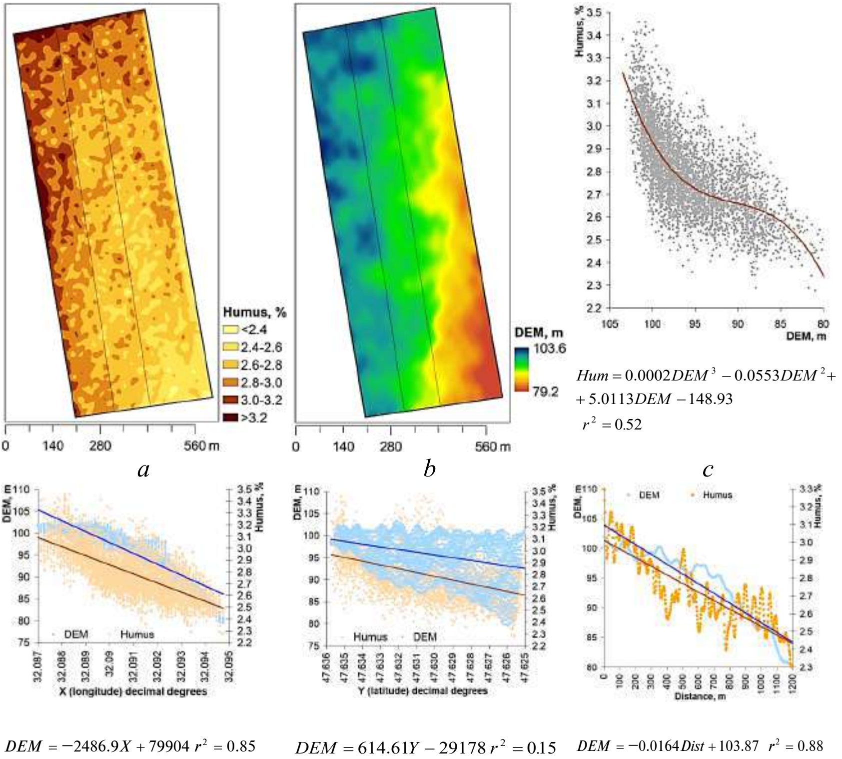


Figure 1. Location of the experimental field and the arrangement of winter wheat crops of the variety Driada 1 according to pre-crops: 1 – pea; 2 – grain crop (spring barley); 3 – sunflower

content in soils ranges from 2.25% to 3.45%, the depth of humus horizon is 50–60 cm, soil density is 1.0–0.2 g/cm^3. The reaction of soil solution is close to neutral (pH 7,0), the amount of absorbed alkali equals 34–38 mg equiv. per 100 g of soil, the degree of saturation with alkali is 95.7%. In terms of the content of mobile macro-elements, the soil of the experimental field is characterized by a medium content of nitrate nitrogen in the soil layer of 0–20 cm – 86.0 mg/kg and that of mobile phosphorous – 58 mg/kg and a very high content of exchangeable potassium – 160.0 mg/kg of soil. The average content of macro-elements equals: manganese – 4.6 mg/kg, zinc – 0.32 mg/kg, cobalt – within 0.02–1.15 mg/kg, cuprum – 0.08–0.59 mg/kg, cadmium – 0.084–0.756 mg/kg, lead – 0.52–5.57 mg/kg, mercury – 0.012 mg/kg of soil.

The terrain affects the distribution of moisture, temperature of soil surface, climate energy for soil formation, determines micro-climatic conditions of crop yield formation within individual fields. Terrain morphology determines the character and intensity of erosion processes resulting in spatial redistribution of agro-chemical elements of soil cover and emergence of parent material on the surface. It is worth mentioning that humus is one of the main characteristics of soil fertility and an indicator of farming efficiency. Decoded satellite imagery of the spacecraft Sentinel 2 and comparison of spectral characteristics with the results of the field research on soil fertility allowed creating a cartogram of humus spatial distribution in the upper layer of 0–20 cm of soil (Fig. 2, *a* (see p. 243)). The cartogram of humus distribution was created using the data of the satellite image dated September 16, 2021, the date of the image creation was characterized by dry soil without vegetation and a lack of moisture for 12–15 days that ensured its accuracy and credibility.

Humus content within the field ranges from 2.25% to 3.45%, the average value is 2.8%. Soil cover disturbance and spatio-temporal differentiation of humus content result from agro-technological processes characterized by intensity of land use. The research established that spatial distribution of humus content in the upper soil layer of 0–20 cm is determined by the terrain and signs of water erosion processes. The terrain of the experimental field lowers from the north-west toward the south-eats within 103.6–79.2 m (Fig. 2, *b*). We established spatial differentiation of humus content in the soil depending on changes in the terrain of the field (Fig. 2, *c*), the level of correlation being $r = 0.72$. It was found that the field lowering by 1 m



$$Hum = 0.0002DEM^3 - 0.0553DEM^2 + 5.0113DEM - 148.93$$
$$r^2 = 0.52$$

$$DEM = -2486.9X + 79904 \quad r^2 = 0.85$$
$$Hum = -77.32X + 2484.1 \quad r^2 = 0.52$$

$$DEM = 614.61Y - 29178 \quad r^2 = 0.15$$
$$Hum = 31.513Y - 1498.2 \quad r^2 = 0.26$$

$$DEM = -0.0164Dist + 103.87 \quad r^2 = 0.88$$
$$Hum = -0.0005Dist + 3.0095 \quad r^2 = 0.73$$

Figure 2. Soil-morphometric characteristic of the experimental field: *a* – a cartogram of humus distribution (%); *b* – a digital model of the terrain (m); *c* – spatial differentiation of humus content in the soil layer of 0–20 cm depending on the terrain of the field; *d* – a change in humus content and the terrain height depending on the values of the territory geographic longitude; *e* – a change in humus content and the terrain height depending on the values of the territory geographic latitude; *f* – a change in humus content and the terrain height from the north-west towards the south-east within the field

is accompanied by a decline in humus content by 0.027% (Fig. 2, *c*, *f* (see p. 243)). Thus, the dependence of a change in humus content on a geographic location of each part of the field and the terrain itself was established (Fig. 2, *d*, *e* (see p. 243)). Humus content is an important indicator of natural soil fertility and an indicator for applying fertilizers, forecasting crop yields, developing methods for improving farming practices.

Agro-technological characteristic of growing winter wheat

The technology of growing winter wheat in the experimental field is presented in Table 1.

Table 1. The technology of growing the winter wheat variety Driada 1 under conditions of the Steppe of Ukraine (2021–2022)

Stages	**Agro-technological practices, specificity**	**Plot 1 (pea pre-crop)**	**Plot 2 (spring barley pre-crop)**	**Plot 3 (sunflower pre-crop)**
1	**2**	**3**	**4**	**5**
Soil tillage	Practice, dates, requirements (depth), notes	▪ disk harrowing of 5–6 cm deep (after harvesting the pre-crop, the 2nd decade of June); ▪ disk plowing of 16–18 cm deep (the 1st decade of August); ▪ tillage of 7–8 cm deep (the 3rd decade of August); ▪ pre-sowing tillage of 5–6 cm deep (the 3rd decade of September).		▪ after harvesting the pre-crop, the 3rd decade of August, disk plowing to 18 cm deep with simultaneous packing down the soil to compress it before sowing winter wheat; ▪ pre-sowing tillage of 5–6 cm deep (the 3rd decade of September).
Seed preparation	Characteristic: generation, emergence, varietal purity, moisture, seed treatment, seeding rate	Sowing certified seeds of the variety Driada of the first generation, their sowing quality complies with the State standards of Ukraine (DSTU 3240-93. Agricultural crop seeds, varietal and sowing characteristics). Winter wheat seeds were treated with the preparation containing the active material Tebukonazol 750 g/kg, 10 days before sowing in the field experiment.		

End of Table 1

1	2	3	4	5
Sowing	Sowing dates, sowing method, equipment, seedbed depth	Seeds were planted with a grain planter with row spacing of 15 cm (C3-5.4) on September 29, the variety Driada 1, its originator is the RPC "Driada LLC", Kherson, Ukraine. The seeding rate was 3.5 mln. of germinating seeds per hectare. The depth of the seedbed was 5–6 cm.		
Caring for crops	Autumn: fight with rodents, spraying. Spring: feeding (fertilizer, rate), feeding dates. Treatment (diseases, herbicides), treatment dates, preparation, equipment, treatment method	Autumn care for the crops involved protection from mouse-like rodents by means of scattering traps treated with a rodenticide with Brodifakum as an active material, 0.25%. Spring care for the crops involved: ▪ early spring feeding of winter wheat plants with mineral fertilizers (nitrate) with the rate N_{30} at the beginning of spring growth; ▪ herbicide to struggle with annual bilobate weeds in agrocenosis (the active material is *Thifensulfuron-methyl*, 300 g/kg + tribenuron-methyl, 300 g/kg + florasulam, 100 g/kg) was applied at the plant growth stage BBCH 30–34; ▪ all insecticide treatments of agrocenosis were performed according to the forecasts of entomophage development (at the stage of grain milk-wax ripeness, insecticide treatment of the crops was performed with the preparation with chlorpyrifos as an active material – 500 g/l and cypermethrin – 50 g/l to prevent the shield bug – ***Eurygaster integriceps Put.***).		
Harvesting	Harvesting dates, harvesting method, grain quality	Winter wheat was harvested in the first decade of July, the grain moisture content being 15%. The yield registration and its structure were performed mechanically, by reaping plants from the registered area with the combine harvester Claas Lexion 760 and recalculating grain moisture content by 14% and impurities – 2%. The area of the registered plots equaled 4,500 m^2.		

Methods for decoding space imagery and spatial analysis

Spatio-temporal differentiation of the vegetation of the winter wheat variety Driada 1 was determined on the basis of calculation of Normalized Difference Vegetation Index (NDVI) (Essaadia et al., 2022; Ding et al., 2022; Beyer et al., 2023) using the data of the decoded space images Sentinel 2 with spatial resolution of the area of 10×10 m per pixel. Vegetation of the variety Driada 1 reflects typical growth processes of winter wheat varieties grown in the Steppe zone of Ukraine.

The value of NDVI was calculated by the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}, \qquad (1)$$

where *NIR* – the visible and near infrared band (Sentinel 2 – Band 8); *Red* – the red band of the electromagnetic spectrum (Sentinel 2 – Band 4).

The images allowed identifying the state of herbage absorbing electromagnetic waves in the visible red band and reflecting them in the near infrared band. In particular, maximum absorption of solar radiation by chlorophyll falls on the red band of the spectrum (the Sentinel 2 central wavelength is 665 nm), and the maximum reflection of energy by leaf cell structure falls on the near infrared band (the Sentinel 2 central wavelength is 842 nm). The imagery decoding made it possible to perform spectral analysis of the distribution of NDVI values and identify spatio-temporal heterogeneity of the development of winter wheat crops. The NDVI values ranged from 0 to 1.0. Bare soil of the field was characterized by the NDVI values from 0.05 to 0.10. The NDVI values at the beginning of sowing equaled 0.10.

The research used space images created in a cloudless sky period. The frequency of image processing was 10–16 days that allowed determining NDVI values for the macro-stages of winter wheat development, namely (Wollmer et al., 2018; Yang et al., 2023): emergence (BBCH 00–09), leaf development (BBCH 10–19), tillering (BBCH 20–29), stem elongation (BBCH 30–39), booting (BBCH 41–49), ear formation (BBCH 51–59), flowering (BBCH 61–69), milk ripeness (BBCH 71–79), wax ripeness (BBCH 81–89) and grain maturation (BBCH 92–99). The correspondence of each NDVI to a certain macro-stage allows observing the development of winter wheat crops with regard to different pre-crops.

In order to visualize cartograms of spatio-temporal distribution of the NDVI values and increase the reliability of interpreting the vegetation index within certain plots and characteristics of heterogeneous winter wheat vegetation, we interpolated the values obtained on the basis of decoding the Sentinel 2 space imagery. Interpolation was carried out using the method of geostatic analysis of radial basis function (Kamińska et al., 2014; Pichura et al., 2023). This deterministic method allowed establishing accurate interpolation surface of the change in the NDVI values retaining the incoming raster data. The correlation and regression method (Riffenburgh, 2006) was used to develop functions of forecasting winter wheat productivity depending on spatio-temporal values of the vegetation index.

To determine changes in the amount of moisture content in winter wheat plants at different stages of their development and establish efficiency of retaining moisture in the plant leaves depending on pre-crops, Normalized Difference Water Index (NDWI) was used (Gao, 1996; Serrano et al., 2019):

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}, \tag{2}$$

where *NIR* – the visible and near infrared band (Sentinel 2 – Band 8A, 865 nm); *SWIR* – shortwave infrared radiation (Sentinel 2 – Band 11, 1,610 nm).

The NDWI values range from −1 to 1. The common range for green vegetation is from −0.1 to 0.4.

Snow cover in winter in the experimental field was identified on the basis of Normalized Difference Snow Index (NDSI) (Sibandze et al., 2014; Riggs et al., 2015):

$$NDSI = \frac{Green - SWIR}{Green + SWIR}, \tag{3}$$

where *Green* – the green band of the electromagnetic spectrum (Sentinel 2 – Band 3, 560 nm); *SWIR* – shortwave infrared radiation (Sentinel 2 – Band 11, 1,610 nm).

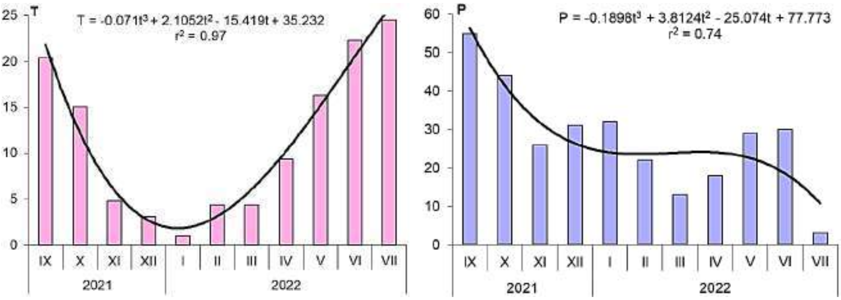
A pixel with the NDSI value >0.0 is considered to contain snow, a pixel with NDSI <= 0.0 is the land surface without snow cover.

Space imagery processing, cartogram creation, spatio-temporal, correlation and regression analyses were performed using the licensed program product ArcGis 10.6 and Microsoft Excel 2010.

RESULTS AND DISCUSSION

Analysis of climatic conditions of the research

The zonal conditions of the research are characterized by semi-arid natural-climatic conditions. The mean air temperature (*T*, °C) in the growing season of the winter wheat variety Driada 1 was 11.4 °C (Fig. 3, *a*), the standard deviation equaled 8.4 °C, the variance level was 74.8%. A high level of the air temperature variance was characterized by seasonal fluctuations. The total precipitation (*P*, mm) in the growing season of winter wheat was 303 mm (Fig. 3, *b*), the standard deviation equaled 14.1 °C, the variance level was 4.7%. Autumn of 2021 in the crop growing season was characterized by sufficient moisture and a moderate temperature regime for the Steppe zone. The total precipitation was 125 mm, the average monthly temperature varied from 20.4 °C in September to 4.8 °C in November, 2021. In this period the air temperature had synchronous fluctuations with precipitation



a *b*

Figure 3. Climatic conditions of the growing season of winter wheat (2021–2022):

a – the average monthly temperature (T, °C);
b – the amount of precipitation (P, mm)

that ensured high germination energy and active photosynthetic processes of the plant development before winter anabiosis.

The winter was characterized by mild climatic conditions with the average monthly temperature of 1.0…4.4 °C and appropriate moisture, the total precipitation was 85 mm. In the second half of December, 2021 and during January, 2022 the satellite images registered a high level of cloudiness within 85–100% above the territory of the experimental field. These months were characterized by a relatively high level of atmospheric moisture, in December the amount of precipitation was 31 mm, in January – 32 mm. Mild temperature conditions and sufficient moisture in winter created favorable conditions for winter anabiosis of winter wheat.

Spring and summer were characterized by typical conditions for the Steppe zone in the growing season of winter wheat. The average monthly air temperature in March equaled 4.4 °C, the level of precipitation was low – 13 mm. Winter wheat resumed growth in the second half of March under the degree days above +5 °C. April of 2022 was characterized by moderate temperature – 9.4 °C, and the amount of precipitation was 18 mm, that accounts for a reduction in activeness of photosynthetic processes and production of chlorophyll content in plants at the macro-stage BBCH 30–36. May was characterized by favorable climatic conditions for winter wheat growth: the average monthly temperature was 16.3 °C, the amount of effective rainfall equaled 29 mm. In particular, there were relatively favorable conditions for plant growth in June, the average monthly temperature equaled 22.3 °C, the amount of effective rainfall was 30 mm. The grain crops were harvested on July 7, 2022, the first decade of July was characterized by high temperatures and lack of precipitation.

Examination of winter wheat growth

Winter wheat growth, activeness of photosynthetic processes, production of chlorophyll content and the formation of yield structural elements depend on soil-climatic conditions of the territory, crop rotation, characteristics of pre-crops and efficiency of agricultural technologies. Satellite imagery decoding and calculation of NDVI values (Fig. 4 (see p. 250), Fig. 5 (see p. 251))

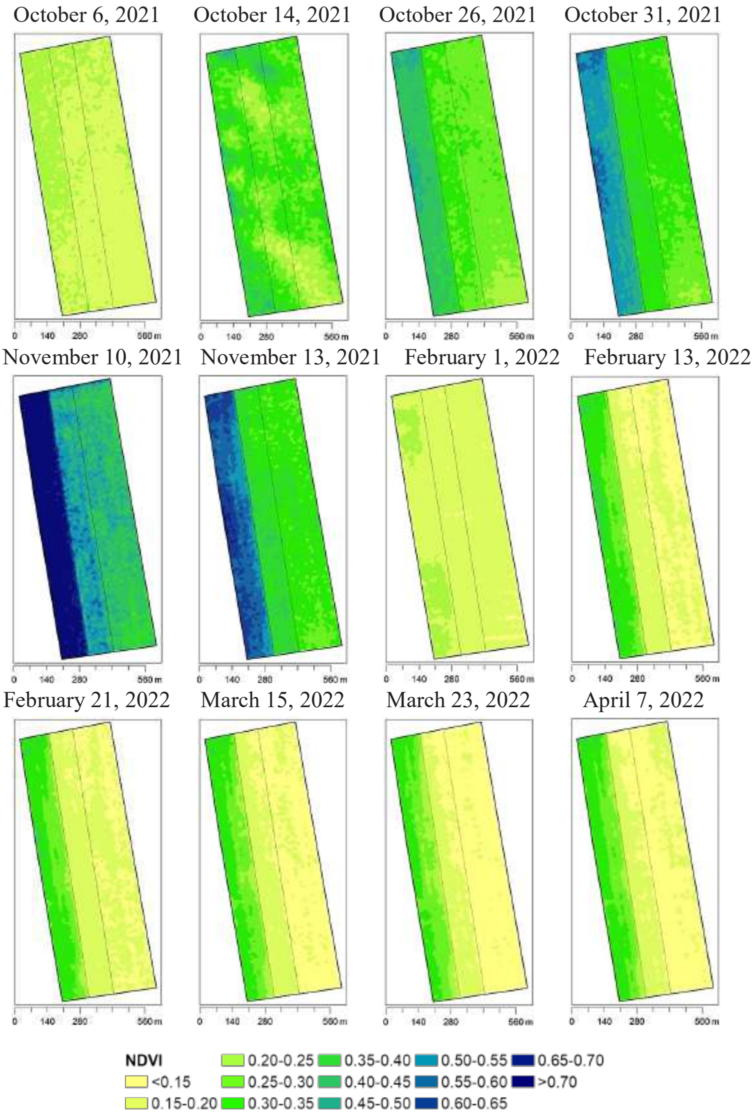


Figure 4. Seasonal differentiation of the NDVI values of the winter wheat variety Driada 1 in the experimental field at the macro-stages BBCH 00–30

allow establishing specificity of plant growth and development at crucial macro-stages of yield formation, that makes it possible to adjust agro-technological operations which can result in an increase in agricultural crop productivity by 40–60%.

Winter crop yields are programmed at the stage of adjusting seeding rates, the recommended seeding rate for winter wheat

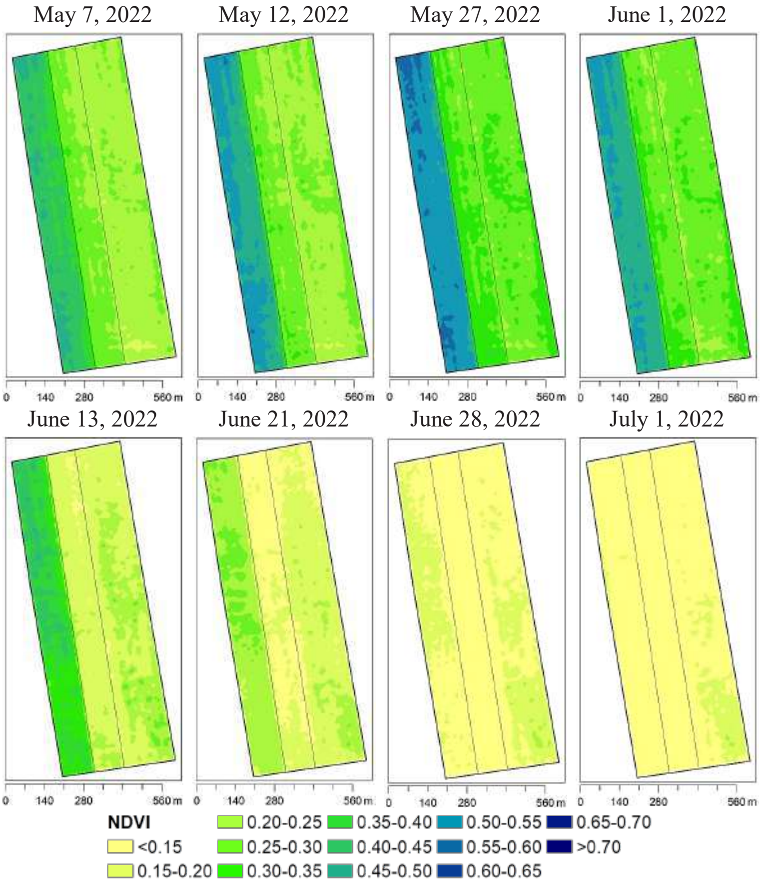
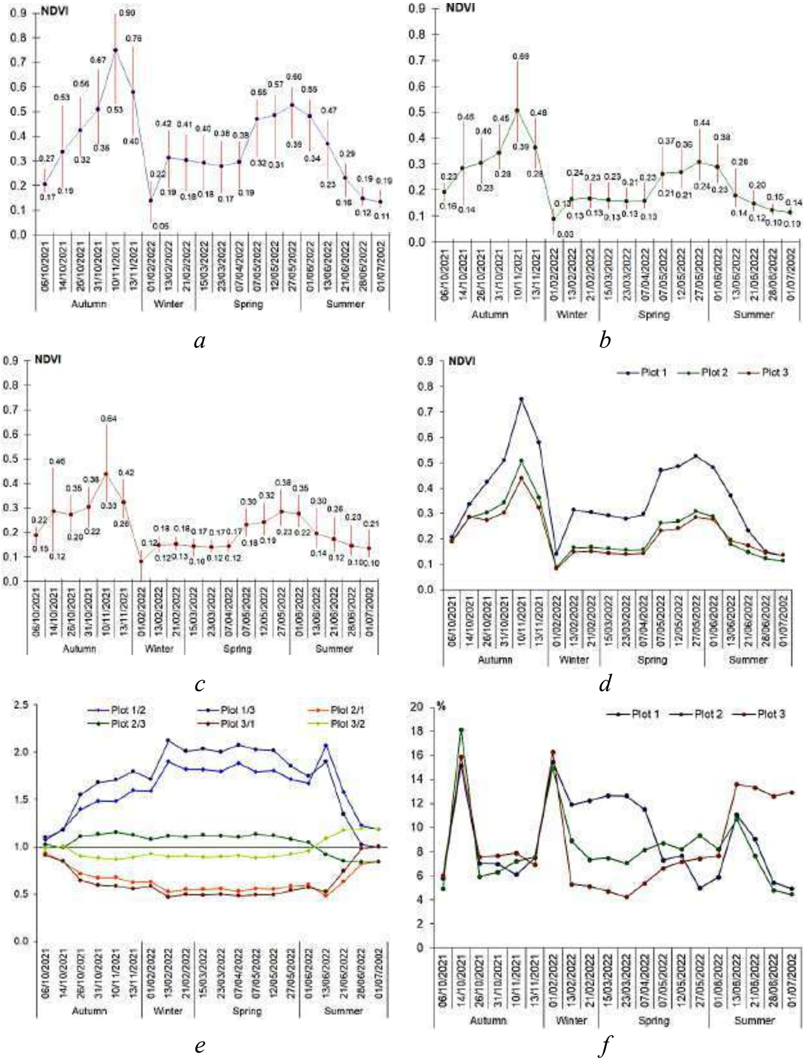


Figure 5. Seasonal differentiation of the NDVI values of the winter wheat variety Driada 1 in the experimental field at the macro-stages BBCH 31–99

in the experimental zone is 3.5 million seeds per hectare. An increase in the seeding rate can cause competition of plants for resources, a decrease in resistance to diseases, a reduction in the level of effective tillering and plant productivity on the whole. On September 29, 2021, at the beginning of sowing the variety Driada 1 (BBCH 00), the average NDVI value of bare soil in the experimental field equaled 0.10. On October 6, 2021 (Fig. 4) there was heterogeneous emergence of winter wheat plants (the micro-stage BBCH 09), the maximum level of NDVI values equaled 0.17–0.27, that was observed on Plot 1 (pea as a pre-crop) (Fig. 4, Fig. 6, *a* (see p. 253)). Worse conditions of plant emergence were registered on Plot 2 (a grain crop (spring barley) as a pre-crop) (Fig. 4, Fig. 6, *b* (see p. 253)) and on Plot 3 (sunflower as a pre-crop) (Fig. 4, Fig. 6, *c* (see p. 253)). The NDVI values varied from 0.16 to 0.19 in 80% of the plot area.

It was established that autumn growth at the macro-stages of leaf development (BBCH 10–19) and tillering (BBCH 20–29) depends on the pre-crop. Favorable conditions for autumn plant development were registered on Plot 1, the NDVI value at the macro-stage BBCH 10–19 increased from 0.19–0.53 to 0.32–0.56 (from October 10 to October 27, 2021). Under insufficient moisture that accounts for extreme conditions of agriculture in the Steppe zone, the macro-stage of autumn tillering in the experimental field lasted till the formation of the fourth tiller (BBCH 20–24). It is worth mentioning that the level of plant photosynthetic processes and the plant density during autumn and spring tillering have accumulative effect of winter wheat yield formation. At the macro-stage BBCH 20–24, on Plot 1, there was a high level of chlorophyll production, the NDVI values during tillering increased from 0.36–0.67 to 0.53–0.90. On November 12, 2021 the crop autumn growth started finishing that was confirmed by a decrease in the NDVI values, in other words, the plants started winter anabiosis.

On Plot 2 stunted growth was observed that prolonged the macro-stages of leaf development (BBCH 10–19) in comparison with the intensity of wheat development in the first field. The duration of the plant growth at the macro-stage BBCH 10–19



a *b*

c *d*

e *f*

Figure 6. Seasonal distribution of the NDVI values of the winter wheat variety Driada 1:

a – Plot 1 (pea as a pre-crop); *b* – Plot 2 (a grain crop (spring barley) as a pre-crop); *c* – Plot 3 (sunflower as a pre-crop); *d* – the average NDVI values; *e* – the correlation of the NDVI values; *f* – the variance of the NDVI values equaled 30 days (October 7 – November 7, 2021). The NDVI values at the stage of leaf development varied from 0.14–0.46 to 0.28–0.45 (Fig. 4, Fig. 6, *b*). The plants on Plot 2 entered winter anabiosis at the macro-stage BBCH 21 (the beginning of tillering and formation of the first tiller). On November 10, 2021 the maximum NDVI value was registered in autumn growth of winter wheat that varied from 0.39 to 0.69.

On Plot 3, with sunflower as a pre-crop, photosynthetic processes slowed down and there was a reduction in the productivity of the winter wheat variety Driada 1. Stunted growth was confirmed by a very low NDVI value (Fig. 6, *c*), the duration of autumn growth at the macro-stage of leaf development. The plants entered winter anabiosis at the macro-stage BBCH 18.

Plant density and the activeness of photosynthetic processes decrease in winter anabiosis. In December, 2021 and January, 2022 there was a high level of cloudiness above the experimental field that did not allow calculating NDVI values. The data of the Meteorological Station Mykolaiv were used for the research, that made it possible to identify a high level of moisture and the temperatures above zero, that created favorable conditions for winter wheat overwintering. At the beginning of February there was a sharp decrease in the NDVI values on the experimental plots, the level corresponded to the values from 0 to 0.22.

Satellite imagery decoding by the Normalized Difference Snow Index (NDSI) and Normalized Difference Water Index (NDWI) on February 1, 2022 (Fig. 7, see p. 255) allowed establishing that a decrease in the NDVI value was determined by snow cover on 25% of the field that changed spectral reflectance characteristics in the near infrared and red bands of the electromagnetic spectrum. On February 13 and February 21, 2022 the satellite images did not register snow cover, that allowed performing accurate calculations of NDVI values for a typical period of winter anabiosis of winter wheat. The NDVI values on Plot 1 varied from 0.18 to 0.42, on Plot 2 – 0.13–0.24, on Plot 3 – from 0.12 to 0.18. It was established that the pre-crop has a considerable impact on activeness of photosynthetic processes during winter anabiosis and plant stress-resistance to climatic conditions.

Winter wheat started resuming spring growth on March 15, 2022 which lasted till April 7, 2022, the NDVI values on Plot 1 varied from 0.17 to 0.38, on Plot 2 – 0.13–0.21, Plot 3 – 0.12–0.17. It is worth mentioning that autumn and spring tillering and the beginning of booting BBCH 30 are important for the formation of productive tillers, ear elements and the amount of future crop yield. In particular, the process of the formation of grain-bearing elements of the ear and the number of grains per ear starts at the end of tillering. At the macro-stage BBCH 30 elongation and segmentation of the growth apex of the second order occur, the formation of the ear rhachis and spikelets in it lasts. This is a sign of moving from the vegetative to generative stage of grain crops. On April 7, 2022 better starting conditions for increasing photosynthetic surface were registered in the winter wheat plants located on Plot 1, the NDVI values equaled 0.19–0.38. Worse

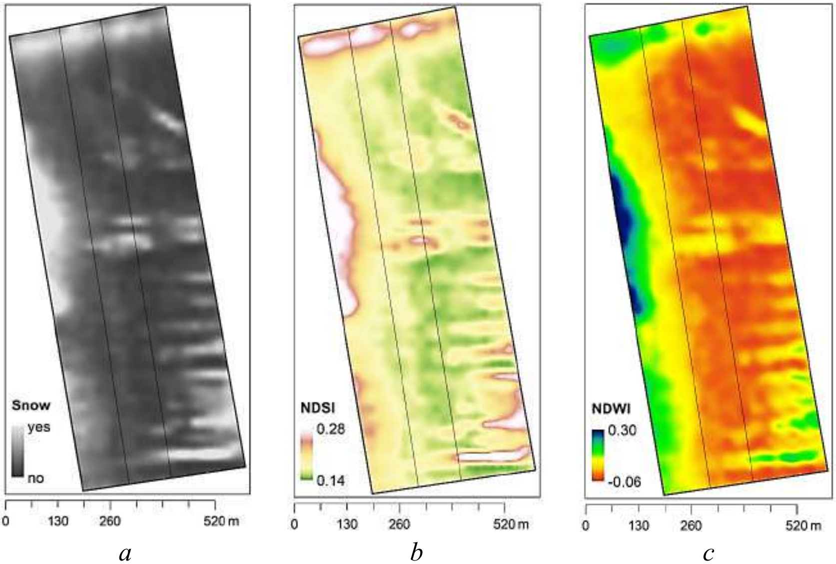


Figure 7. Indication of the presence of snow cover (NDSI) and moisture (NDWI) of the experimental field on February 1, 2022:
a – presence of snow cover; *b* – Normalized Difference Snow Index (NDSI); *c* – Normalized Difference Water Index (NDWI)

conditions were observed in the plants on Plot 2, the NDVI values being 0.13–0.23, and on Plot 3, the NDVI values being 0.12–0.17.

At the beginning of booting (the macro-stage BBCH 30–34) flowers start forming in the spikelets and the ear starts growing intensively. It is a crucial period of growth and development of grain crops. Therefore, ammonium nitrate at the rate N_{30} was added in early spring and the herbicide with the active material Thifensulfuron-methyl, 300 g/kg + trybenuron-methyl, 300 g/kg + florasulam, 100 g/kg was applied according to schedule. Such agro-technological practices contribute to an increase in the number of viable productive shoots, that prevent dieback of the existing productive stems, have a positive effect on individual plant productivity and optimal plant density, protect crops from diseases and pests at the time of booting, that results in an increase in the ear productivity of grain crops.

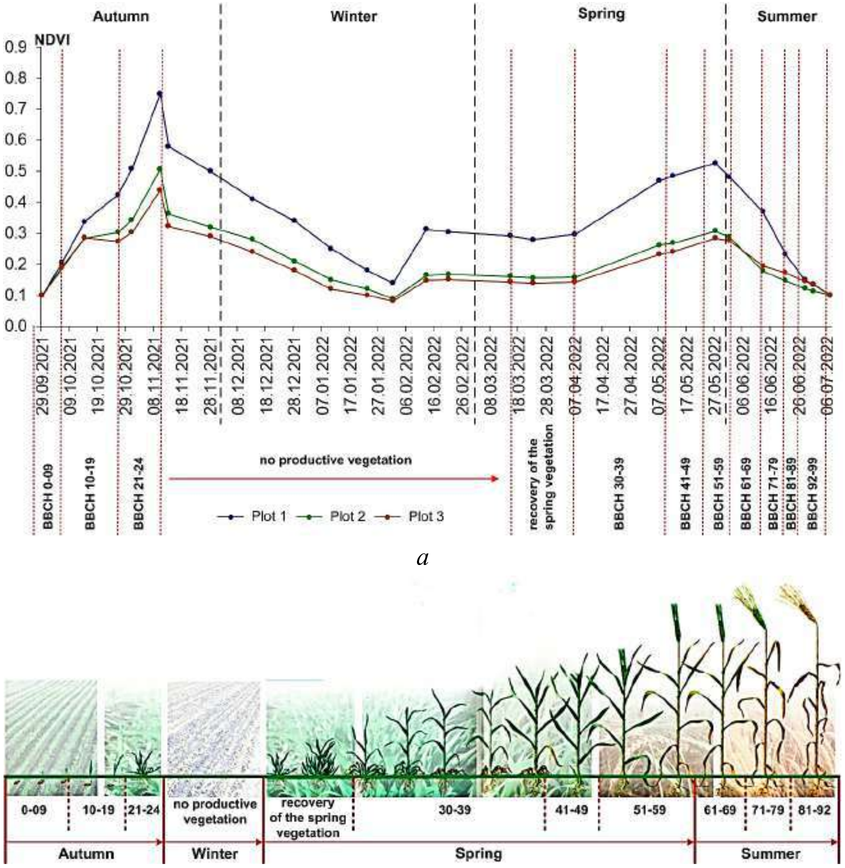
To protect leaves of grain crops using chemical control is an important agro-technological task, since leaf diseases are a cause of a decrease in the area of photosynthetic surface during the vegetative stage, that is a reason for too early cessation of photosynthetic processes, a reduction in the activeness of chlorophyll production, crop yield and productivity. Therefore, efficient absorption of photosynthetic radiation and an active increase in the biomass of grain crops begins with the emergence of the third leaf (BBCH 32) and lasts till the end of milk ripeness (BBCH 79). Therefore, in this period, realization of genetic potential of winter wheat depends on the effectiveness of agro-technological practices aimed at protecting plants against diseases, fertilization regime and moisture retention. In particular, the state of productive shoots is important at the macro-stages of stem elongation (BBCH 30–39) and booting (BBCH 41–49), that insures highly-productive formation of plant photosynthetic surface. The number of productive stems per unit area (m^2), the number of spikelets and grains per ear, the weight of 1,000 seeds (grain-unit) are important indicators of winter wheat productivity. The following results were obtained on the experimental plots: Plot 1 – the yield was 4.65 t/ha, the number of productive stems was 390 pcs/m^2, the weight of 1,000 seeds – 42.5 g, the number of grains per ear – 30 pcs, the weight of grain per ear – 1.27 g; Plot 2 – the yield was 3.24 t/ha, the number of productive stems was 320 pcs/m^2, the weight of 1,000 seeds – 39.0 g, the number of grains per ear – 27 pcs, the weight of grain per ear – 1.05 g; Plot 3 – the yield was 2.98 t/ha, the weight of 1,000 seeds – 39.0 g, the number of productive stems was 305 pcs/m^2, the number of grains per ear – 26 pcs, the weight of grain per ear – 1.01 g.

It was established that after heading (BBCH 37–39) in the flag leaf and the pre-flag leaf (BBCH 31–33), and also in the ear (BBCH 59) there occurs synthesis of reserve material which is transported and accumulated in the kernel endosperm. The weight of a grain and the weight of 1,000 grains depend on the efficiency of this physiological process. The formation of 45% of the total grain weight is supported by assimilates formed in the flag leaf. The pre-flag leaf, the second, third and fourth leaves form grains to 35%, the rest 20% is formed from accumulated assimilates and synthesized in the ear.

In the period of the flag leaf formation on May 7, 2022 (Fig. 5, Fig. 6) the NDVI values of the crops on Plot 1 varied from 0.32 to 0.55, on Plot 2 – within 0.21–0.37, on Plot 3 – 0.18–0.30. It was established that in the period of the flag leaf formation, the supply of assimilates to the ear on Plot 1 was 1.8–2.0 times higher than the corresponding process on Plots 2 and 3 that accounts for the formation of higher ear productivity with pea as a pre-crop. During the booting macro-stage BBCH 41–49 there was a similar tendency for an increase in the NDVI values and better conditions for the formation on Plot 1. The period of the ear emergence (BBCH 51–59) and synthesis of assimilates in the ear is an important macro-stage for the formation of 20% of winter wheat productivity. The maximum increase in photosynthetic surface of the crops was registered in this period. The maximum activeness of photosynthetic processes and chlorophyll production in winter wheat crops was registered on Plot 1, the NDVI values on May 27, 2022 were within 0.39–0.60. Lower NDVI values were observed on Plot 2 – from 0.24 to 0.44, and Plot 3 – within 0.23–0.38. At the end of the macro-stages of the ear emergence and the start of flowering (BBCH 61–69) there was a reduction in activeness of photosynthesis, the NDVI value on Plot 1 varied from 0.34 to 0.55, on Plot 2 – 0.23–0.38, on Plot 3 – 0.22–0.35. Flowering is an important stage of organogenesis when plants move from the generative stage of development to the reproductive stage, pollination of flowers in the spikelets occurs and the process of the kernel formation starts. Therefore, plant damage by diseases, fusariosis in particular, and pests in this period is a cause of a decrease in the number of grains per ear, their weight and quality (gluten content).

In the first weeks after flowering the formation of kernels in the ear occurs lasting till the end of the micro-stage of milk ripeness (BBCH 79). In this period 50% of organic matter is synthesized and it comes to the kernel, therefore prolongation of the period of active photosynthetic processes and maximum retention of leaf assimilation surface are a necessary condition for obtaining high yields. These processes can be supported by fertilization and plant protection against diseases. At the end of the stage of milk ripeness (BBCH 79) and at the beginning of the macro-stage of wax ripeness (BBCH 81), on June 21, 2022, the NDVI values were similar, on Plot 1 they varied from 0.16 to 0.29, on Plot 2 – within 0.12–0.20, on Plot 3 – from 0.12 to 0.26. It was an indicator of cessation of the process of absorbing photosynthetic radiation by the plants and the beginning of grain maturation. At the macro-stage BBCH 92–99, on July 1, 2023, the NDVI value in the experimental field equaled 0.11–0.19. The state of the crops at the micros-stage BBCH 93 “Grains poorly hold the ear in the daytime” became an indicator of the necessity of harvesting. The crops were harvested on July 7, 2022. The average yield of the winter wheat variety Driada 1 was as follows: on Plot 1 – 4.65 t/ha, Plot 2 – 3.24 t/ha, Plot 3 – 2.98 t/ha.

Spatio-temporal seasonal decoding of the satellite imagery and calculation of the NDVI values allowed establishing that winter wheat plants on Plot 1 with pea as a pre-crop grew 1.6 times more actively (Fig. 6) than those on Plot 2 (a grain crop (spring barley) as a pre-crop), and 1.7 times more actively than those on Plot 3 (sunflower as a pre-crop). In this way an increase in winter wheat productivity was registered on Plot 1 in comparison with the productivity on Plots 2 and 3, 1.43 and 1.56 times respectively. The characteristics are given in Fig. 8. The results of the research on the impact of pre-crops on seasonal changes of NDVI values of winter wheat in accordance with the unified BBCH scale (Fig. 8) prove the dependence of winter wheat growth, the formation of productivity of photosynthetic surface, activeness of photosynthetic processes and chlorophyll production under identical climatic conditions and agro-technological practices of the crop cultivation on the pre-crop.



a

b

Figure 8. Changes in NDVI (*a*) and visualization (*b*) of winter wheat development in accordance with the unified BBCH scale

Forecasting winter wheat yield

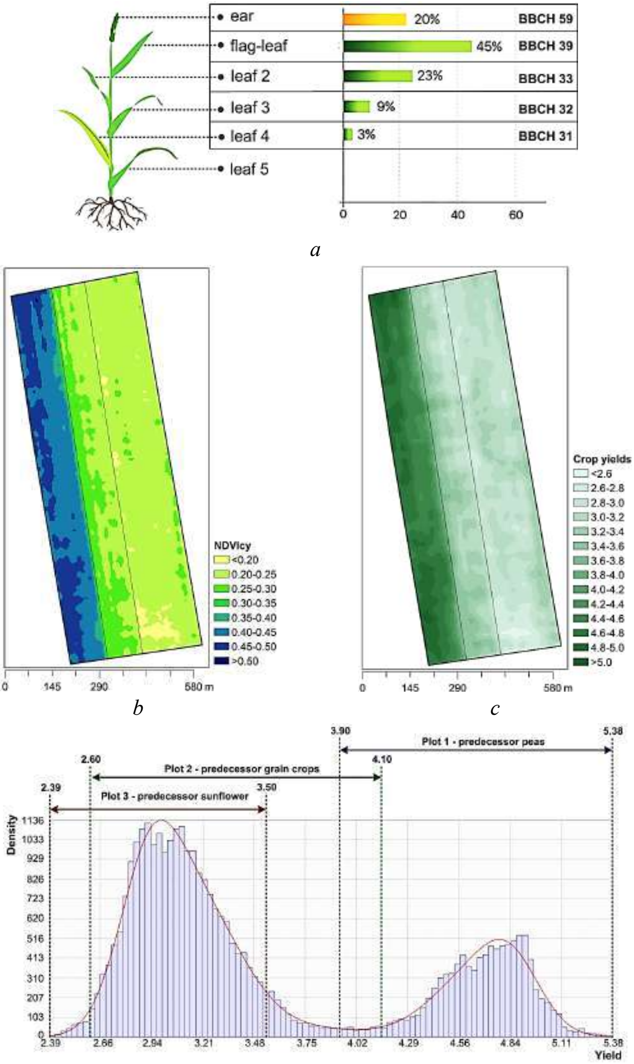
Application of the results of the decoded satellite imagery and calculation of NDVI values in the growing season of winter wheat allows performing approximation of the vegetation curve of plant development aimed at establishing effectiveness of using agro-technological practices, forecasting winter wheat yields depending on the pre-crop and the level of plant growth at the critical macro-stages of gaining biomass that determine the level of productivity. It was established that the following periods are important for the formation of winter wheat yields: leaf production and accumulation of assimilates by the plant (Fig. 9, *a* (see p. 261)) at the stage of the development of 4–2 leaves (BBCH 31–33), the flag leaf (BBCH 37–39) and the ear (BBCH 59). On the basis of approximation of the NDVI values in the period of crucial stages for the vegetative formation of winter wheat yields, a generalized cartogram of spatial distribution of NDVI_{cy} (Fig. 9, *b* (see p. 261)) was created by the formula:

$$\begin{aligned} NDVI_{cy} &= 0.03NDVI_{BBCH\,31} + 0.09NDVI_{BBCH\,32} + \\ &+0.23NDVI_{BBCH\,33} + 0.45NDVI_{BBCH\,39} + 0.2NDVI_{BBCH\,59}. \end{aligned} \quad (4)$$

The formula takes into account the share of each micro-stage of the plant growth in winter wheat productivity. In particular, the cartogram characterizes the degree of a pre-crop impact, soil-morphometric and climatic conditions of the area, effectiveness of agro-technological practices in the growth process and grain formation.

In order to specify the correspondence of the NDVI_{cy} level to the amount of the yield, the NDVI_{cy} values were standardized by means of mathematical relation of raster values of the vegetation index to its average value for each plot by the pre-crop. Calculations allowed creating raster surfaces, in which the value “1” corresponded to the average NDVI_{cy} value of an individual plot. In turn, the average NDVI_{cy} value of a plot corresponded to the average value of winter wheat yield.

These data were used to create cartograms of spatial differentiation of winter wheat yields (*CY*) of the variety



a

b *c*

d

Figure 9. Yield formation of the winter wheat variety Driada 1:
a – crucial stages of yield formation; *b* – cartograms of distribution of the generalized NDVI data; *c* – cartogram of yield distribution; *d* – histogram of yield distribution

Driada 1 (Fig. 9, *c* (see p. 261)) with regard to the distribution of the standardized NDVI_{cy} values by the formula:

$$CY = \frac{NDVIi_{cy}}{Aver(NDVIi_{cy})} \times Aver(CY_i)\,, \tag{5}$$

where $NDVIi_{cy}$ – the vegetation index value within individual experimental plots of a pre-crop; $Aver(NDVIi_{cy})$ – the average vegetation index value within individual experimental crops of the pre-crop; $Aver(CY_i)$ – the average value of winter wheat yields within individual experimental plots of the pre-crop.

The cartogram of winter wheat yields allows identifying heterogeneous productivity of the variety Driada 1 depending on the pre-crop. It was established that winter wheat yields on Plot 1 (pea as a pre-crop) vary from 3.90 to 5.38 t/ha (Fig. 9, *d* (see p. 261)), on Plot 2 (a grain crop (spring barley) as a pre-crop) – within 2.60–4.10 t/ha, on Plot 3 (sunflower as a pre-crop) – from 2.39 to 3.50 t/ha.

A mathematical model of the yield formation of the winter wheat variety Driada 1 depending on the pre-crop by the main stages of production and accumulation of assimilates in plants was developed:

Pea as a pre-crop:

$$\begin{gathered} Y_1 = 1.735NDVI_{32} + 2.040NDVI_{33} + 4.813NDVI_{39} + 2.139NDVI_{59}, \\ r^2 = 0.999. \end{gathered} \tag{6}$$

A grain crop (spring barley) as a pre-crop:

$$\begin{gathered} Y_2 = 2.238NDVI_{32} + 2.420NDVI_{33} + 5.925NDVI_{39} + 2.633NDVI_{59}, \\ r^2 = 0.999. \end{gathered} \tag{7}$$

Sunflower as a pre-crop:

$$\begin{gathered} Y_3 = 2.180NDVI_{32} + 2.550NDVI_{33} + 6.030NDVI_{39} + 2.680NDVI_{59}, \\ r^2 = 0.999. \end{gathered} \tag{8}$$

It was determined that four micro-stages are important generative stages of plant development for winter wheat yield formation, therefore the yields of the winter wheat variety Driada 1 were forecasted on the basis of the data of spatial differentiation of NDVI values at the micro-stages: BBCH 32, BBCH 33, BBCH 39 and BBCH 59. Functions allowed for a high level of approximation of the actual data at the level of 99.9%, that confirms their high reliability for forecasting winter wheat productivity depending on the pre-crop.

CONCLUSIONS

The research on winter wheat development and productivity in natural-climatic conditions of the Steppe zone depending on the pre-crop was carried out during the growing season of winter wheat (autumn 2021 and winter, spring and the beginning of summer 2022). Spatio-temporal processes of winter wheat growth in accordance with the unified BBCH-scale were examined on the basis of the data of the decoded series of satellite imagery of the spacecraft Sentinel 2 and calculation of NDVI values. It was established that the growth of winter wheat crops on Plot 1 (pea as a pre-crop) was 1.6 times more active than on Plot 2 (a grain crop (spring barley) as a pre-crop) and 1.7 times more active than on Plot 3 (sunflower as a pre-crop). Thus, active growth led to an increase in winter wheat productivity on Plot 1 in comparison with winter wheat productivity on Plots 2 and 3, 1.43 and 1.56 times respectively. Winter wheat productivity on Plot 1 with pea as a pre-crop was 4.65 t/ha, on Plot 2 with a grain crop (spring barley) as a pre-crop – 3.24 t/ha, on Plot 3 with sunflower as a pre-crop – 2.98 t/ha.

It was proved that the formation of 45% of the total grain weight is provided by assimilates in the flag leaf. The pre-flag leaf, the second, third and fourth leaves take part in the formation of the grain by 35%, the rest 20% is synthesized from accumulated assimilates in the ear. The weight of each grain, the weight of 1,000 seeds and crop yields depend on the efficiency of synthesis of reserve substances which are further transported and accumulated in the kernel endosperm. Therefore, mathematical models of forecasting winter wheat productivity depending on the pre-crop were created on the basis of the cartograms of spatial differentiation of NDVI values, during the period of this physiological process at the macro-stages BBCH 32, BBCH 33, BBCH 39 and BBCH 59. The credibility of modelling was 99.9%.

The obtained research results can be used to improve methods for studying agricultural crop growth, substantiate crop-rotations and pre-crops, determine effectiveness of agro-technological practices and forecast winter wheat productivity in soil-climatic conditions of the Steppe zone of Ukraine.

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REGULARITIES OF VEGETATIVE FORMATION OF WATER BALANCE IN WINTER WHEAT AGROCENOSIS DEPENDING ON A PRE-CROP ACCORDING TO THE BBCH SCALE UNDER NON-IRRIGATED CONDITIONS OF THE STEPPE ZONE

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INTRODUCTION

Food security, which is a determining factor of global stability, is an important task of agricultural production. The main reasons for agricultural producers' concern are climate changes, whose intensification complicates farming. It is important to highlight that, over the past years, introduction of adaptive technologies and use of stress-resistant varieties and hybrids of agricultural crops are difficult to access for small farms because of high prices for seeds, plant protection products, fuels and lubricants and high depreciation of machines. Large enterprises took dominating positions on the market of agricultural products that has led to deterioration of ecological condition of land and water resources, caused by introduction of intensive technologies (Breus et al., 2021, 2022; Dudiak et al., 2020, 2021; Pichura et al., 2021a).

Intensive agriculture means introducing technologies for growing agricultural crops aimed at improving their productivity (Bruns, 2012; Siddique et al., 2021) that has become a cause of increasing genetic homogeneity and similarity of agricultural landscapes (Hufnagel et al., 2020; Sehgal et al., 2023). It was established (USDA-ERS…, 2012; Skok et al., 2023) that application of balanced systems of crop rotations involving rotation of crops with high and low levels of residues in one field is an important method for coping with such problems. Crop rotations including legume crops contribute to an increase in productivity of a subsequent crop, maintaining nitrogen balance due to its fixation in soil (Claassen et al., 2018). Therefore, application of crop rotations increases resistance of soil systems to abiotic and biotic stresses (Reckling et al., 2016; Li et al., 2019; Sanford et al., 2021). Consequently, crop rotations improve plant growth, water balance of agrocenoses, water-table and soil moisture content and contribute to a rise in agricultural crop productivity (Stetina et al., 2007; Bennett et al., 2012).

It was found (Albers et al., 2017; Knapp et al., 2018; Domaratskiy et al., 2018, 2019) that the main conditions for vegetation are a climatic factor, crop rotations, the amount of nutrients in soil and the level of agro-technological practices. In particular, a pre-crop affects the level of accumulation of nutrients important for plants in soil, moisture content in soil, sowing dates, intensity of vegetation, formation of morphological properties and leaf water balance, the rate of plant metabolism and photosynthesis (Berzsenyi et al., 2000; Yang et al., 2022; Breus et al., 2023). An effective pre-crop improves a field microclimate, that is maintained by an increase in leaf surface of crops and a reduction in evaporation of moisture from soil surface (Ray et al., 2015; Berti et al., 2016). It was proved (Firn et al., 2019) that functional characteristics of leaves directly correlate with plant growth and productivity. They affect the carbon cycle, dynamics and energy balance of natural and artificial ecosystems. Plants with small leaf area and low nitrogen content in leaves have slow photosynthetic output (Cui et al., 2020). In particular, optimization of photosynthetic, gas-exchanging, water-accumulating, filtrating and water-supplying leaf potential maintains conditions for better absorption of atmospheric carbon by plants (Deans et al., 2020).

Development of crops of a certain variety or hybrid depends on changes in the environment (Reichstein et al., 2014; Anderegg et al., 2018) and agro-technological conditions of crop cultivation. It is determined by signs of plasticity which manifests itself in the state of plant leaves (Rozendaal et al., 2006; Doughty et al., 2018;

Yang et al., 2019) under the influence of biotic and abiotic factors. Well-developed plant plasticity is a result of selection and adaptation of varieties and hybrids to particular soil-climatic conditions for growing them (Domaratskiy et al., 2022; Pichura et al., 2023a). In addition, plant breeding is important for agrocenosis adaptation to new climatic conditions occurring over the past 25–30 years. Therefore, understanding the processes of leaf development under changeable conditions is crucial in correcting their breeding characteristics and adaptation of agro-technological methods.

It was established (Wang et al., 2022) that moisture content in leaf tissues is an important functional characteristic of plants. Water determines bio-chemical reactions, regulates plant growth and metabolism affecting agrocenosis productivity, the carbon cycle in agro-ecosystems and adjacent territories. Water has an immediate effect on other leaf characteristics, first of all, thermo-regulation, the rate of photosynthesis and leaf surface area. A change in leaf surface area determines micro-climatic conditions for plant vegetative growth and their productivity that is important for zones with rainfall deficit and high air temperatures.

It is necessary to emphasize an increasing frequency of climate anomalies and rising risks of their negative effect. The main symptom of climate change is a drop in the level of moisture supply against a background of significant warming (Dudiak et al., 2019; Pichura et al., 2021b, 2022). Moisture has become a determining factor in all soil-climatic zones of Ukraine (Korkhova et al., 2023). Consequently, the problem of retaining soil moisture and increasing plant resistance to moisture deficit is topical. In this context, it is necessary to focus on improving agro-technological methods, substantiating selection of a pre-crop for increasing nutrients in soil and creating favorable micro-climatic conditions for vegetative growth of plants, accumulating and retaining moisture in soil and leaf cells, high photosynthetic capacity of plants and agrocenosis productivity. Studies on balanced crop rotations do not have sufficient information about spatio-temporal regularities of vegetative formation of water balance in agrocenoses according to the unified BBCH scale that complicates substantiation of the necessity to improve the system of agricultural crop cultivation in zones of moisture deficit and risky farming. The purpose of the research in this direction is to develop recommendations and introduce necessary practices aimed at increasing the level of crop rotation efficiency for obtaining economic and environmental benefits by agricultural producers.

Agricultural crop production in the Steppe zone is characterized by three main directions: growing grain, oil-bearing and legume crops. Crop rotations with a share of grain crops up to 70–80% dominate. Grain crops mainly include winter wheat, spring barley, winter barley and corn. Therefore, regularities of vegetative formation of water balance in agrocenoses depending on a pre-crop were established using winter wheat crops under non-irrigated conditions of the Steppe zone of Ukraine.

RESULTS AND DISCUSSION

Examination of vegetative formation of water balance in winter wheat crops

The level of crop productivity mainly depends on soil moisture content, which is necessary for seed germination and plant rooting, absorption of nutrients by plants and appropriate functioning during the vegetation period. In order to maintain the potential of productivity under conditions of a drier climate, soil tillage and a pre-crop play a key role in accumulating and retaining moisture and in creating optimal conditions for growth and development of the root system.

Under global warming, a fall in the amount or precipitation, application of conventional soil tillage and a lack of a balanced crop rotation are the reasons for significant losses of soil moisture, a deterioration in plant growth and agrocenosis productivity. Therefore, optimization of agro-technological methods contributes to better moisture accumulation and appropriate consumption by plants, and reduces the level of unproductive losses because of evaporation. Calculation of the NDWI values (Fig. 1, 2 (see p. 273–274)) by means of decoded satellite images allows establishing regularities of vegetative formation

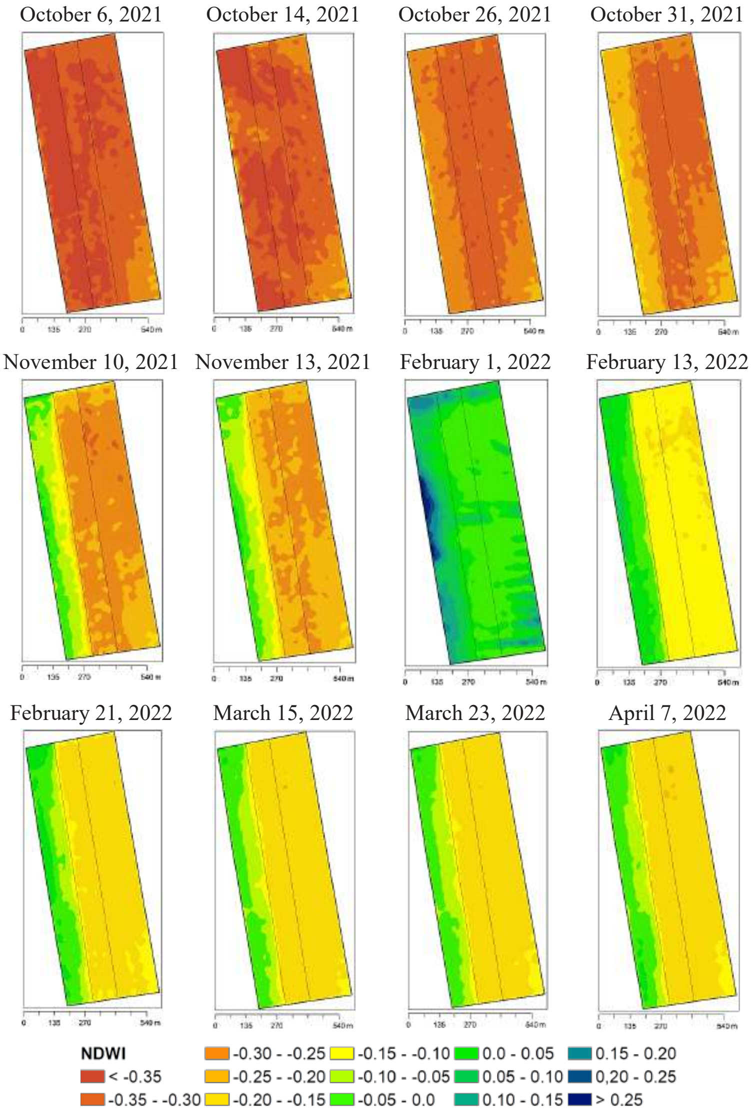
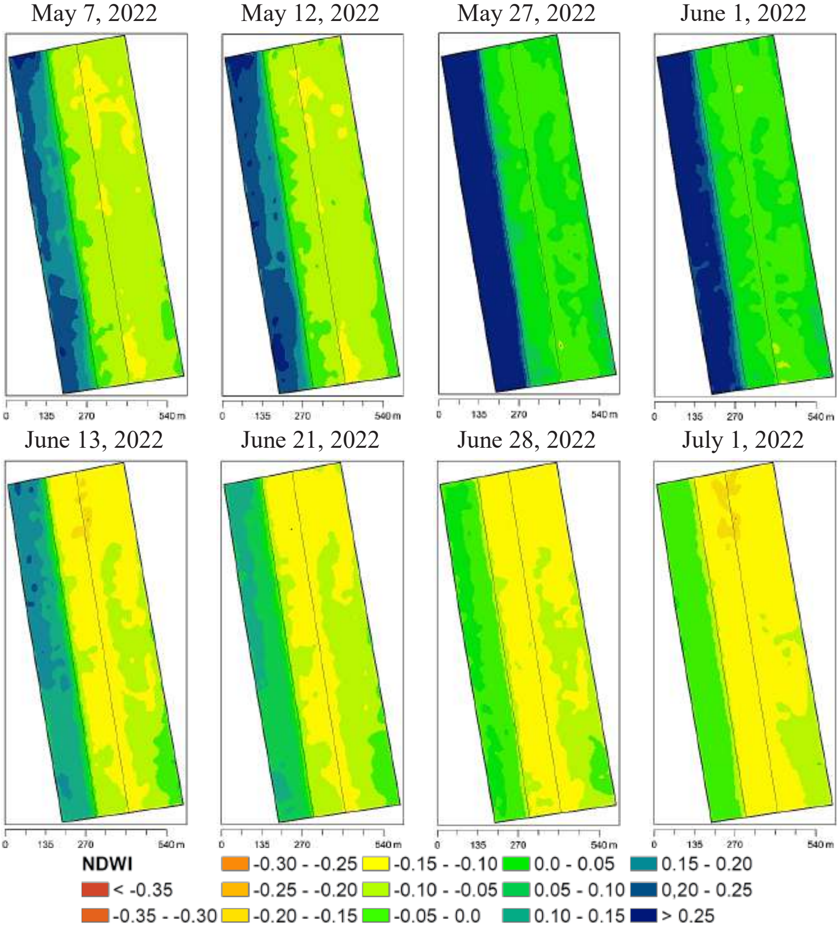


Figure 1. Seasonal differentiation of the NDWI values of the winter wheat variety Driada 1 in the experimental field at the macro-stages BBCH 00–30

of water balance in winter wheat crops depending on a pre-crop, specificity of the formation of a field micro-climate and plant development according to the unified BBCH scale, calculating spatial differentiation of plant water consumption and retention of productive moisture supply in soils.



May 7, 2022 · May 12, 2022 · May 27, 2022 · June 1, 2022

June 13, 2022 · June 21, 2022 · June 28, 2022 · July 1, 2022

Figure 2. Seasonal differentiation of the NDWI values of the winter wheat variety Driada 1 in the experimental field at the macro-stages BBCH 31–99

At the beginning of sowing the winter wheat variety Driada 1 (BBCH 00) productive moisture reserves in the soil layer of 0–30 cm in the experimental field ranged from 14.5 to 24.3 mm, and it fluctuated between 55.4 and 92.4 mm in a meter soil layer. On October 6, 2021 (Fig. 1) at the beginning winter wheat sprouting (the macro-stage BBCH 09), the NDWI values ranged from −0.38 to −0.24 (Fig. 1, Fig. 3). At this time the emergence rate depended on moisture accumulated in the top soil of 0–10 cm. The period of autumn vagetation at the macro-stage of leaf development (BBCH 10–19) and tillering (BBCH 20–29) depends on a pre-crop. On Plot 1 there were favorable conditions for autumn plant development, the NDWI value at the macro-stage BBCH 10–19 increased from −0.35 to −0.28 (from October 7 to October 27, 2021). The satellite image dated October 26, 2021 shows accelerated process of moisture accumulation in plants on Plot 1 and in the north-eastern part of Plot 3, that is determined by the relief of the plot. Due to an insufficient level of moisture content that determines extreme conditions of agriculture in the Steppe zone, the macro-stage of autumn tillering had lasted in the experimental field by the time of formation of the fourth tiller (BBCH 20–24). During this period, on Plot 1, there was a relatively high level of water balance in winter wheat crops, the NDWI values over the period of tillering increased from −0.28 to −0.08; the maximum value at the end of the macro-stage of autumn tillering equaled 0.11, autumn vegetation ceased that was confirmed by the NDVI values and plants started going dormant.

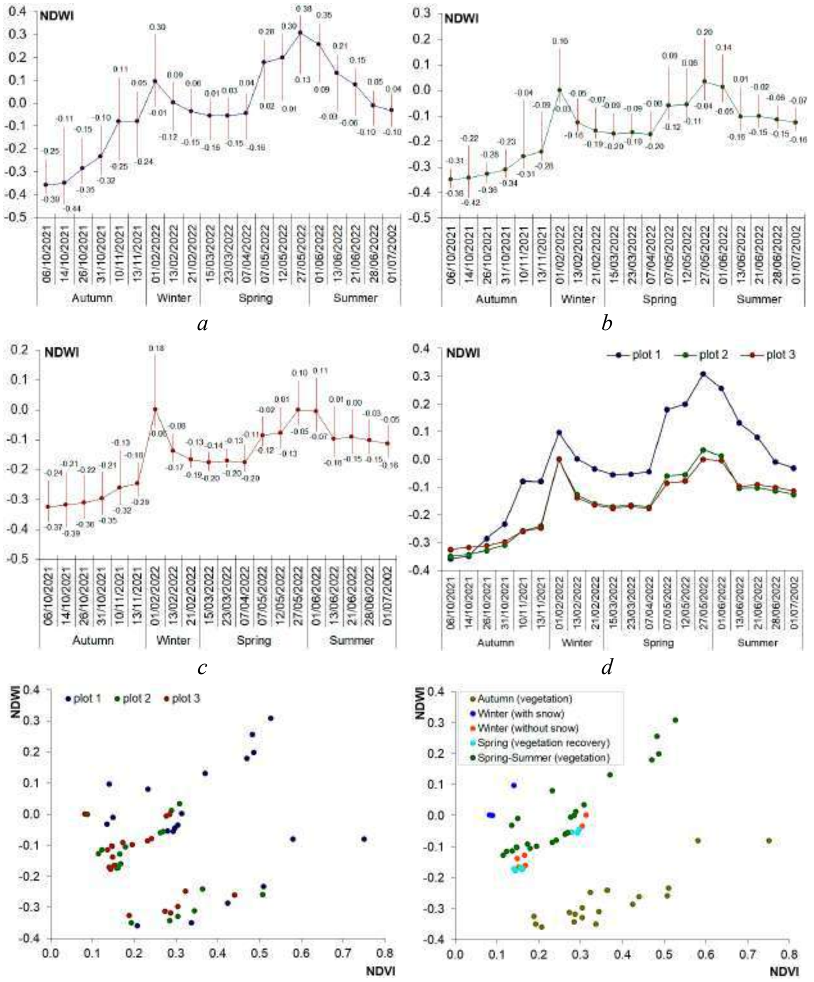
On Plot 2 there was suppression in vegetation that prolonged the duration of the macro-stage of leaf development (BBCH 10–19) in comparison with the intensity of winter wheat development on Plot 1. The period of plant vegetation at the macro-stage BBCH 10–19 lasted 30 days (October 7 – November 7, 2021). It was determined by a low level of accumulated water in leaves, a low level of photosynthetic processes and leaf surface area. The NDWI values at the stage of leaf development ranged from −0.34 to −0.26 (Fig. 1, Fig. 3, *b*). Plants on Plot 2 started going dormant at the macro-stage BBCH 21, the NDWI value ranged from −0.28 to −0.09.

On Plot 3 there was suppression in winter wheat vegetation, moisture deficit in leaves and slower metabolic chemical reactions in plants. It caused an increase in the duration of the period of autumn vegetation at the macro-stage of leaf development and the beginning of winter dormancy at the macro-stage BBCH 18. The NDWI value ranged from −0.29 to −0.18 (Fig. 1, Fig. 3, *c*).

In December, 2021 and January, 2022 there was a high level of cloudiness above the experimental field that did not allow calculating the NDWI values. Therefore, the data of Mykolaiv land meteorological station were used for the research that allowed establishing a high level of moisture supply and temperature values above zero that created favorable conditions for winter wheat wintering. At the beginning of February there was a sharp increase in the NDWI values on the experimental plots, that was evident in changes in the index values from −0.06 to 0.30. High NDWI values from 0.16 to 0.30 were registered on the plots covered with snow.

From February 13 to February 21, 2022 the satellite images did not register any snow cover that allowed performing accurate calculations of the NDWI of moisture retention in plant leaves in winter. It was established that a pre-crop has a considerable impact on the formation of water balance inf winter wheat crops and stress-resistance to changes in winter temperatures. The NDWI values on Plot 1 ranged from −0.15 to 0.09, on Plot 2 – from −0.19 to −0.05, on Plot 3 – from −0.19 to −0.08.

The renewal of spring vegetation of winter wheat started on March 15, 2022 and lasted till April 7, 2022, the NDWI values ranged from −0.16 to 0.03 on Plot 1 (Fig. 1, Fig. 3, *a* (see p. 277)), from −0.20 to −0.09 on Plot 2 (Fig. 1, Fig. 3, *b* (see p. 277)), from −0.20 to −0.13 on Plot 3 (Fig. 1, Fig. 3, *c*). The level of productive moisture fluctuated between 90.0 and 165.6 mm in the soil layer of 0–100 cm at the time of vegetation renewal. It is necessary to highlight that the periods of autumn and spring tillering and the beginning of booting BBCH 30 are very important for the formation of productive stems, ear elements and crop yields. During this stage, elongation and segmentation of the growing-point



a *b*

c *d*

e *f*

Figure 3. Seasonal distribution of the NDWI of the winter wheat variety Driada 1:

a – Plot 1 (pea as e pre-crop); *b* – Plot 2 (a grain crop as a pre-crop); *c* – Plot 3 (sunflower as a pre-crop); *d* – mean NDWI values; *e* – differentiation of the NDWI values depending on the NDVI of winter wheat according to pre-crops; *f* – differentiation of the NDWI values depending on the NDVI values of winter wheat in each season and phenological stages of development occur (vegetative cone), the formation of the ear rachis and spikelets in it continues. It is an indicator of transition from a vegetative to a generative stage of grain crop development. Therefore, the level of accumulated water in leaves at the stage BBCH 30 is an indicator of productive transition from a vegetative to a generative stage of grain crop development.

On April 7, 2022 the highest level of water in winter wheat leaves was registered on Plot 1 (Fig. 2, Fig. 3, *d* (see p. 277)), that created better initial conditions for increasing plant photosynthetic surface, the NDWI values being from −0.16 to 0.04 (Fig. 3, *a*). Worse conditions were observed in the plants on Plot 2 with the NDWI values ranging from−0.20 to −0.08 (Fig. 3, *b*), and Plot 3, the NDWI values being from −0.20 to −0.11 (Fig. 3, *c* (see p. 277)).

At the beginning of the stage of booting (the macro-stage BBCH 30–34), the formation of flowers in ears and active growth of the ear occur, that is a crucial period of growth and development of grain crops. At this time, agro-technological practices contribute to an increase in the number of viable productive shoots which prevent dieback of productive shoots, have a positive effect on individual plant productivity and optimal plant density, protect crops from diseases and pests at the time of booting, resulting in an increase in the ear productivity of grain crops.

An important agro-technological task is to protect grain crop leaves with chemical plant protection products, since leaf diseases are the reason for a reduction in moisture in plants, in photosynthetic surface area during vegetation that causes an earlier cessation of photosynthetic processes, a fall in activeness of chlorophyll production and a decline in crop productivity. Therefore, effective absorption of photosynthetic radiation and active growth of grain crop biomass starts with the emergence of the third leaf (BBCH 32) and lasts till the completion of milk ripeness (BBCH 79). In this period, genetic potential of winter wheat is realized. It also depends on effectiveness of agro-technological practices aimed at protection of plants against diseases and pests, plant feeding schedules and moisture retention. In particular, the state of productive shoots affecting productivity of plant photosynthetic surface is important at the macro-stages of stem elongation (BBCH 30–39) and booting (BBCH 41–49). It was established that after heading (BBCH 37–39), in the flag leaf (BBCH 31–33) and in the ear (BBCH 59), reserve substances, which are further transported and accumulated in kernel endosperm, are synthesized. The weight of a grain and the weight of 1,000 grains depend on efficiency of this physiological process. Formation of 45% of the total grain weight is maintained by assimilates emerging in the flag leaf. The first, second, third and fourth leaves form 35% of the grain, the other 20% is formed from accumulated assimilates and synthesized in the ear.

In the period of the flag leaf formation, on May 7, 2022 (Fig. 2, Fig. 3), the NDWI values on Plot 1 ranged from 0.02 to 0.28, on Plot 2 – from −0.12 to 0.09, on Plot 3 – from −0.12 to −0.02. It was established that water balance in winter wheat crops on Plot 1 is 3.0–4.0 times higher than the corresponding value on Plots 2 and 3 in the period of the flag leaf formation. It determined an increase in assimilates coming to the ear on Plot 1 – 1.8–2.0 times and the formation of high ear productivity with pea as a pre-crop. At the macro-stage of booting BBCH 41–49, there was a tendency for an increase in the NDWI and there were favorable conditions for moisture accumulation on Plot 1. The period of ear emergence (BBCH 51–59) and synthesis of assimilates in the ear is an important macro-stage. Maximum growth of plant photosynthetic surface was registered in this period. The maximum water level in leaves, activeness of photosynthetic processes and chlorophyll production of winter wheat crops were registered on Plot 1, the NDWI value fluctuated between 0.13 and 0.38 on May 27, 2022. Lower NDWI values were registered on Plot 2: from −0.04 to 0.20 and on Plot 3: from−0.05 to 0.10. At the end of the macro-stages of ear emergence and the beginning of flowering (BBCH 61–69), there was a reduction in moisture content in plants and a decline in photosynthetic activeness, the NDWI values on Plot 1 ranged from 0.09 to 0.35, on Plot 2 – from −0.05 to 0.14, on Plot 3 – from−0.07 to 0.11. Flowering is an important stage of organogenesis, when there occurs transition from a generative stage of plant development to a reproductive stage, marked by pollination of flowers in spikelets and the beginning of the process of kernel formation. At the macro-stage BBCH 51–61 there was a maximum value of water accumulation in plants for the entire period of vegetation which is an indicator of possible winter wheat productivity. It was established that the NDWI value is 8.5–9.0 times higher than the corresponding value on Plots 2 and 3 at the peak of water balance formation in winter wheat on Plot 1 with pea as a pre-crop. It confirms favorable micro-climatic conditions of moisture supply, an increase in stress-resistance to changes in the temperature regime, a reduction in the level of moisture evaporation from soil surface, retention of productive moisture reserves in soils for growing subsequent crops.

During the first weeks after flowering, kernels emerge in the ear that lasts till the end of the micro-stage of milk ripeness (BBCH 79). 50% of organic matter is synthesized and comes to kernels in this period, therefore, moisture retention being a factor of prolongation of photosynthetic activeness and maximum maintenance of assimilating leaf surface, is an indispensable condition for obtaining high yields. These processes are possible due to fertilization and plant protection against diseases. At the end of the stage of milk ripeness (BBCH 79) and at the beginning of the macro-stage of wax ripeness (BBCH 81), on June 21, 2022, the NDWI values on Plot 1 considerably excessed the corresponding value on Plots 2 and 3 (Fig. 2, Fig. 3), that is an evidence of favorable conditions for grain formation. A further decline in water balance in winter wheat crops is an indicator of cessation of the process of plant absorption of photosynthetic radiation and the beginning of ripening. On July 1, 2022, at the macro-stage BBCH 92–99, the NDWI value ranged from −0.16 to 0.04. The state of crops at the micro-stage BBCH 93 “Grain loosening in daytime” is an indicator of the beginning of harvesting. Crops were harvested on July 7, 2022. It was established that the average productivity of the winter wheat variety Driada 1 equals: on Plot 1 – 4.65 t/ha, on Plot 2 – 3.24 t/ha, on Plot 3 – 2.98 t/ha.

Previous research found regularities of the impact of pre-crops on winter wheat vegetation on the basis of calculation of the NDVI by the unified BBCH scale. It allowed establishing regularities of the NDWI differentiation depending on the NDVI of winter wheat according to a pre-crop (Fig. 3, *e* (see p. 277)), seasons and phenological stages of development (Fig. 3, *f* (see p. 277)).

Functions of the NDWI differentiation depending on the NDVI in different seasons and phenological stages of the winter wheat variety Driada 1 are as follows:

Autumn (vegetation): $NDWI = 0.4958NDVI - 0.4583 \quad r^2 = 0.78$. (1)

Winter (with snow): $NDWI = 1.7337NDVI - 0.1459 \quad r^2 = 0.99$. (2)

Winter (without snow): $NDWI = 0.8698NDVI - 0.2847 \quad r^2 = 0.94$. (3)

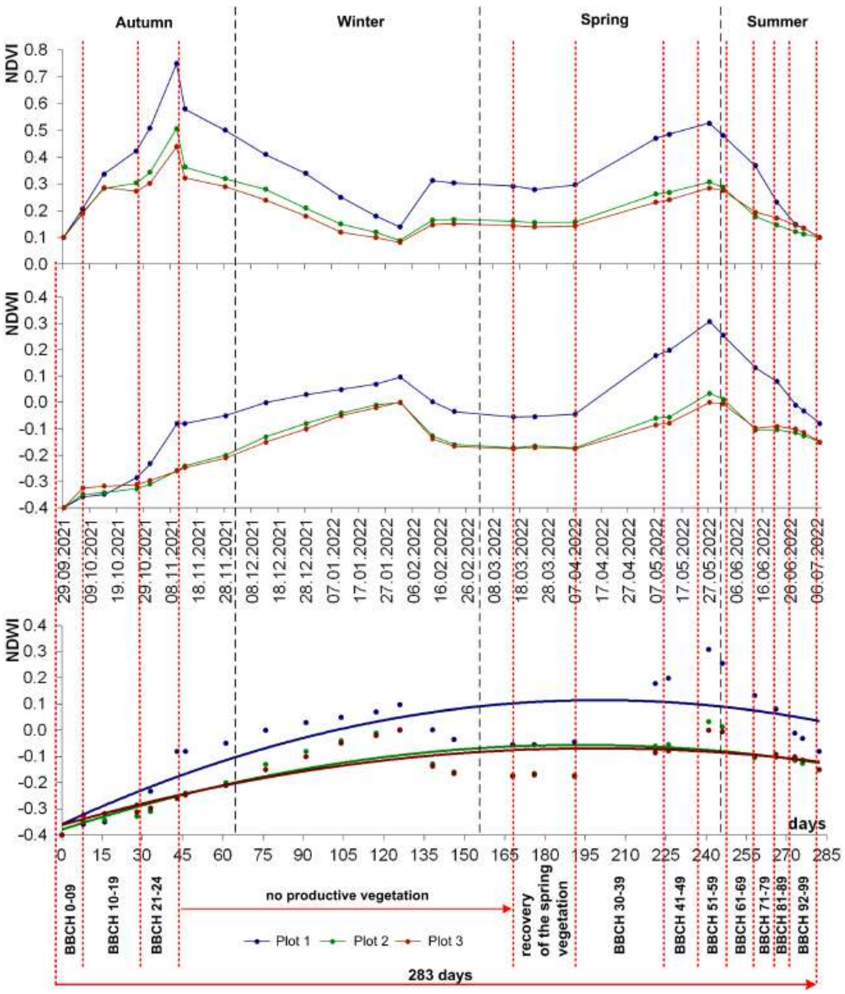
Spring (vegetation recovery): $NDWI = 0.8606NDVI - 0.3008 \quad r^2 = 0.99$. (4)

Spring-Summer (vegetation): $NDWI = 0.9361NDVI - 0.2414 \quad r^2 = 0.86$. (5)

It was established that a pre-crop affects growth of a subsequent crop, the rate and amount of water accumulated in leaves, photosynthesis intensity, leaf surface area, the metabolic rate and the formation of winter wheat productivity. It was established that the best vegetation, formation of morphological properties and water balance of leaves were observed in the crops with pea as a pre-crop at all the stages of plant development (Fig. 3, *e*). For instance, in the vegetation period in autumn, at the macro-stage (BBCH 10–24), the average NDVI value fluctuated between 0.21 and 0.75 and the NDWI value ranged from −0.36 to −0.08 on Plot 1; the NDVI value fluctuated between 0.19 and 0.51 and the NDWI value ranged from −0.35 to −0.24 on Plot 2; the NDVI value fluctuated between 0.19 and 0.44 and the NDWI value ranged from −0.32 to −0.25 on Plot 3. In the period of winter dormancy, in the period without snow the situation was the following: the NDVI value equaled 0.30–0.31 and the NDWI value ranged from −0.03 to 0.0 on Plot 1; the NDVI value equaled 0.16 and the NDWI value fluctuated between −0.17 and −0.13 on Plot 2; the NDVI value equaled 0.15 and the NDWI value ranged from −0.17 to −0.14 on Plot 3. At the renewal of spring vegetation, the NDVI value ranged from 0.27 to 0.29 and the NDWI value fluctuated between −0.06 and −0.05 on Plot 1; the NDVI value equaled 0.16 and the NDWI was −0.17 on Plot 2; the NDVI value equaled 0.14 and the NDWI value was at the level −0.18 on Plot 3. In the spring-summer period of vegetation, at the macro-stage (BBCH 30–93), the average NDVI value fluctuated between 0.29 and 0.53 and the NDWI value ranged from −0.05 to 0.31 on Plot 1; the NDVI value fluctuated between 0.11 and 0.31 and the NDWI value ranged from −0.11 to 0.03 on Plot 2; the NDVI value fluctuated between 0.14 and 0.28 and the NDWI value ranged from −0.10 to 0.0 on Plot 3. The research allowed establishing seasonal regularities of water accumulation in winter wheat plants (Fig. 3, *f*), in particular, in the autumn period of vegetation, at the macro-stage (BBCH 10–24), the NDWI value fluctuated between −0.36 and −0.08, in the period of winter dormancy with snow cover, it ranged from 0 to 0.10 and without snow cover – from−0.17 to 0, in the period of the renewal of spring vegetation it ranged from −0.18 to −0,05, in the spring-summer period of vegetation, at the macro-stage (BBCH 30–93), it fluctuated between −0.11 and 0.31.

The obtained functions allow identifying specificity of the formation of water balance in winter wheat and its vegetative accumulation in agrocenoses leaves depending on seasonal-phenological stages of plant vegetation in typical soil-climatic conditions in the Steppe zone of Ukraine. The obtained results can be used in forecasting accumulation and water consumption in crops depending on a pre-crop, in evaluating the impact of a pre-crop on crop vegetation, that will allow predicting winter wheat yields.

On the basis of the results obtained by means of spatio-temporal seasonal decoding of satellite imagery and calculations of the NDWI values, it was established that the formation of water balance of winter wheat agrocenosis on Plot 1 with pea as a pre-crop occurred 3.0–9.0 times more actively than on Plots 2 and 3 (Fig. 4, see p. 283). In particular, vegetation of winter wheat plants by the NDVI on Plot 1 with pea as a pre-crop occurred 1.6 times more actively than on Plot 2 (a grain crop (spring barley) as a pre-crop), and



Pea as a pre-crop: $NDWI = 0.1 \times 10^{-4} t^2 + 0.0047t - 0.3592 \quad r^2 = 0.70$

Spring barley as a pre-cop: $NDWI = 0.9 \times 10^{-5} t^2 + 0.0033t - 0.3798 \quad r^2 = 0.72$

Sunflower as a pre-crop: $NDWI = 0.7 \times 10^{-5} t^2 + 0.0029t - 0.3623 \quad r^2 = 0.71$

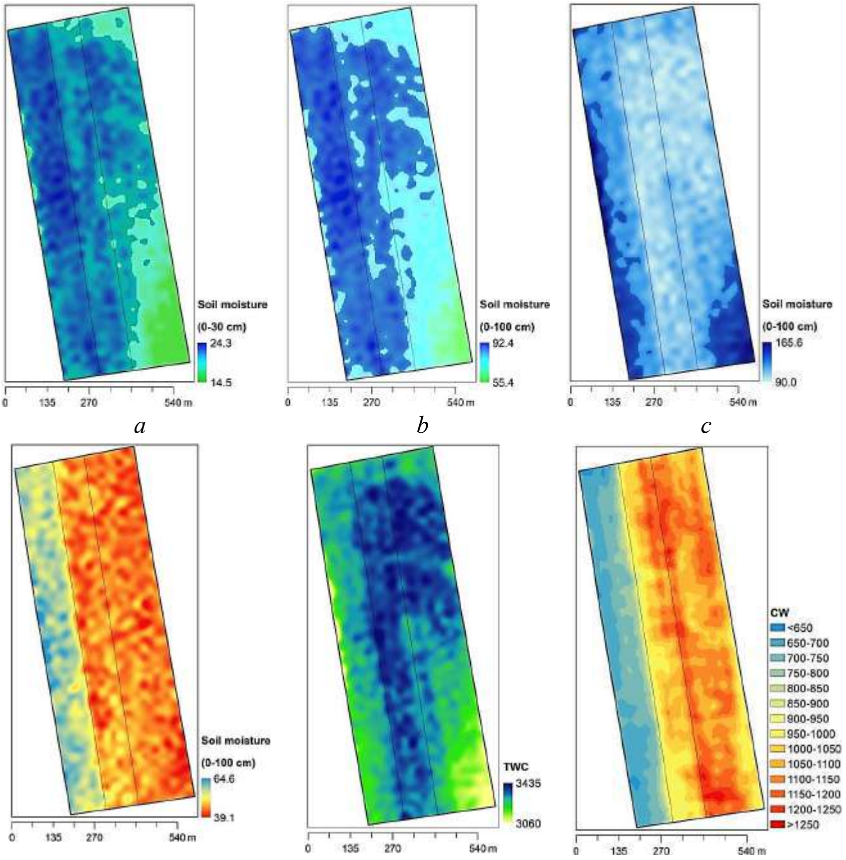
Figure 4. Changes in the NDVI and the NDWI values of winter wheat according to the unified BBCH scale

1.7 times more actively than on Plot 3 (sunflower as a pre-crop). As a result, there was an increase in winter wheat productivity on Plot 1 in comparison with productivity on Plots 2 and 3 – 1.43 and 1.56 times, respectively. It was found that the rate of increase in moisture reserves in plant leaves at the macro-stages BBCH 10–61 on Plot 1 is 1.54 and 1.82 times higher than the corresponding value on Plots 2 and 3. The research established a positive effect of a pre-crop on winter wheat vegetation, water balance, productivity of plant photosynthetic surface, activeness of photosynthetic processes, chlorophyll production that manifests itself in an increase in productivity of agricultural crops.

The research allowed drawing a conclusion about environmental and economic benefits of crop rotations, the capability to reduce the use of productive moisture reserves in soils and increase their resistance in the zone of moisture deficit and extreme agriculture. First of all, retention of moisture in soils enhances their biological condition, intensifies humification and restores fertility, improves physical-chemical properties, reduces the impact of erosion processes, creates favorable initial conditions for growing subsequent crops. Therefore, determination of the level of productive moisture in soils at the beginning and at the end of the vegetation period and calculation of the coefficient of plant water consumption depending on a pre-crop are important factors of forecasting productivity of agricultural crops.

At the beginning of winter wheat planting, productive moisture reserves in the soil layer of 0–30 cm in the experimental field ranged from 14.5 to 24.3 mm (Fig. 5, *a* (see p. 285)). About 70% of the field area was characterized by a sufficient level of moisture content in the upper layer (21–30 mm of productive moisture reserves), 30% of the field area was characterized by an insufficient level of moisture content (11–20 mm of productive moisture reserves).

It was established that productive moisture reserves in a meter soil layer equaled 55.4–92.4 mm (Fig. 5, *b* (see p. 285)). About 57% of the field area was characterized by a sufficient level of moisture content in a meter soil layer (81–120 mm of productive moisture reserves), 43% of the field area was characterized



a *b* *c*

d *e* *f*

Figure 5. Differentiation of productive moisture reserves (mm) in the soils of the experimental field and water consumption (m^3/t) by winter wheat plants:

a – moisture at the beginning of sowing in the soil layer of 0–30 cm, mm; *b* – moisture at the beginning of sowing in the soil layer of 0–100 cm, mm; *c* – moisture at the time of the renewal of vegetation in the soil layer of 0–100 cm, mm; *d* – soil moisture at the end of vegetation in the soil layer of 0–100 cm, mm; *e* – total water consumption in the vegetation period, m^3/t; *f* – water consumption per 1 t of yield, m^3/t by an insufficient level of moisture content (51–80 mm of productive moisture reserves). The largest part of the filed with an insufficient level of moisture content at the beginning of winter wheat planting is located in slightly-eroded soils with low contents of clay.

The examined period of winter dormancy of winter wheat was characterized by mild climatic conditions and a high level of atmospheric moisture supply for the Steppe zone of Ukraine. The total precipitation in winter equaled 85 mm that contributed to additional accumulation of moisture and maintained sufficient (81–120 mm of productive moisture reserves) and optimal (more than 120 mm of productive moisture reserves) levels of soil moisture in the layer of 0–100 cm (Fig. 5, *c* (see p. 285)) and sufficient climate energy at the renewal of spring vegetation of winter wheat. Productive moisture reserves under the crops at the end of vegetation in the soil layer of 0–100 cm (Fig. 5, *d* (see p. 285)) ranged from 39.1 to 64.6 mm, in particular: on Plot 1 – from 44.0 to 64.6 mm; on Plot 2 – from 42.0 to 52.7 mm; on Plot 3 – from 39.1 to 50.3 mm. It was found that Plot 1 with pea as a pre-crop had productive moisture reserves higher by 18% and 20% at the end of vegetation in a meter soil layer than on Plots 2 and 3, respectively. It was established that the total water consumption of winter wheat in the vegetation period ranged from 3,060 to 3,435 m^3 (Fig. 5, *e* (see p. 285)). In particular, water consumption for the formation of a ton of wheat grain (Fig. 5, *f* (see p. 285)) on Plot 1 fluctuated between 630 and 975 m^3/t, on Plot 2 – from 860 to 1,226 m^3/t, on Plot 3 – from 925 to 1,286 m^3/t. In other words, on Plot 1 with pea as a pre-crop, water consumption for the formation of a ton of winter wheat grain is less by 30.5% and 34.3% than on Plots 2 and 3, respectively. It was established that using pea in crop rotations in the zone of risky farming is an effective agricultural practice since it contributes to better vegetation of a subsequent crop, the formation of good morphological properties of plants and water balance, an increase in plant resistance to stressful climatic-conditions, a rise in agrocenosis productivity and an increase in productive moisture reserves in soils of farmlands. In particular, saturation of crop rotations with pea has environmental and economic benefits that manifest themselves in higher agrocenosis productivity, a reduction in the rates of nitrogen fertilizers with a corresponding increase in profitability of agricultural commodity producers.

CONCLUSIONS

The study examined spatio-temporal processes of vegetation and the formation of water balance in winter wheat agrocenosis depending on a pre-crop according to the unified BBCH scale under non-irrigated conditions of the Steppe zone of Ukraine. It was found that the formation of water balance in winter wheat agrocenosis on Plot 1 with pea as a pre-crop according to seasonal-phenological stages of plant vegetation occurs 3.0–9.0 times more actively than on Plot 2 with a grain crop (spring barley) as a pre-crop and on Plot 3 with sunflower as a pre-crop. In particular, plant vegetation of winter wheat crops on Plot 1 occurred 1.6 more actively than on Plot 2 and 1.7 times more actively than on Plot 3. Consequently, there was an increase in winter wheat productivity on Plot 1 in comparison with winter wheat productivity on Plots 2 and 3 – 1.43 and 1.56 times, respectively. It was established that the rate of increase in moisture reserves in plant leaves at the macro-stages BBCH 10–61 on Plot 1 was 1.54 and 1.82 times higher than the corresponding value on Plots 2 and 3. It was proved that water consumption for the formation of a ton of grain with pea as a pre-crop is by 30.5% and 34.3% less than on Plots 2 and 3, respectively. It resulted in a 20% increase in productive moisture reserves at the end of vegetation in a meter soil layer on Plot 1. It was proved that using pea in crop rotations in the zone of risky farming determines nitrogen fixation in soil that improves conditions for vegetation of a subsequent crop, contributes to the formation of morphological properties and leaf water balance, an increase in the metabolic rate and plant photosynthesis, a better field micro-climate, a reduction in intensity of evaporation and use of productive moisture reserves in soil, an increase in stress-resistance of soil systems and higher productivity of agricultural crops. The obtained research results can be used to improve methods for examining vegetation of agricultural crops, substantiating crop rotations, managing resources, developing adaptive-climatic agricultural technologies, forecasting agricultural crop productivity and profitability of economic activity of enterprises in the soil-climatic conditions of the Steppe zone of Ukraine.

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BIOLOGIZATION OF GROWTH TECHNOLOGIES OF WINTER WHEAT IN THE CONDITIONS OF SOUTH STEPPE OF UKRAINE

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INTRODUCTION

In the production of food products, agricultural technologies influence efficiency in many aspects, including ecological-geographical and economic factors, as well as the replenishment of biological resources. Active research is conducted in various fields of biological sciences to enhance biological productivity in agriculture. Biological methods are used to improve soil fertility, control pests and diseases of cultivated plants, and the role of biotechnology is constantly increasing, both in specific aspects and in improving the overall efficiency of traditional agricultural technologies (Herasymenko et al., 2006).

In particular, in grain production, the combination of traditional chemical methods with new biological elements becomes extremely important, including the use of mineral fertilizers together with innovative microbiological agents. The application of rhizosphere microorganisms for the fixation of biological nitrogen from the atmosphere by diazotrophic bacteria is of great importance for compensating the nitrogen deficit in plant nutrition. This also contributes to increased soil productivity, reduced costs for synthetic mineral fertilizers, and improved ecological characteristics of agricultural landscapes. The biologization of the agricultural sector allows the production of environmentally friendly and economically viable crop production, the preservation of soil fertility, and the enhancement of the ecological resilience of agricultural landscapes (Yulevych et al., 2012).

In recent years, significant progress has been made in the development of biological agents based on associative microorganisms with complex action. The microorganisms included in these biological agents perform various functions that contribute to increased crop yields while growing agricultural crops (Satarova et al., 2016).

Ukraine has also been actively studying the interaction between plants and microorganisms under modern conditions. This is particularly relevant due to restrictions on the use of mineral and organic fertilizers and plant protection agents, as well as the simplification of agricultural technologies. In such conditions, it is important to find additional sources to compensate the losses, and one of them is the use of complex-action biological agents, including those based on rhizosphere microorganisms. Apart from nitrogen fixation, these microorganisms produce physiologically active compounds that promote the growth and development of plants. Recent research has also identified new strains of microorganisms that can suppress the development of pathogenic microflora, thereby reducing the risk of plant diseases, increasing crop yields, and improving the quality of agricultural products (Volkohon et al., 2006).

According to modern research, associative diazotrophs form exospheric associations on plant roots (Patyka et al., 2004). This creates interactions among plants, microbial populations, and external factors, including the conversion of atmospheric nitrogen into nitrogen compounds available to plants (biological nitrogen) (Kozhemiakov, 1997).

To achieve the effective use of biological agents, it is important to create optimal conditions in the soil for the intensive multiplication of diazotrophs in the plant rhizosphere. This can be done using substrates and organic products of photosynthesis (Khomenko, 2009).

The association between the roots of winter wheat and diazotrophs in the Steppe region of Ukraine can fix up to 50–60 kg of atmospheric nitrogen per hectare and even more. In addition to nitrogen fixation from the atmosphere, associative diazotrophs are capable of producing various physiologically active substances such as auxins, gibberellins, and cytokinins. These substances promote the improvement of the root system, increase the root's absorptive capacity, stimulate the development of plant reproductive organs, and inhibit the activity of phytopathogenic microorganisms.

The productivity of nitrogen-fixing diazotrophs largely depends on the soil moisture level. They can fix nitrogen from the atmosphere at temperatures ranging from 5 to 40 °C, with the optimal temperature being in the range of 20…30 °C. These microorganisms can also thrive in soils with pH levels ranging from 5.6 to 8.0.

To carry out the process of nitrogen fixation, rhizosphere bacteria utilize products of plant photosynthesis, such as organic substances, root exudates, and decaying roots, as their primary source of energy. Depending on the plant species, it takes from 4.1 to 24.2 grams of carbohydrates to fix one gram of nitrogen. Therefore, diazotrophs can efficiently fix nitrogen only in collaboration with plants that actively undergo photosynthesis, such as wheat.

Mineral nitrogen in the soil and small doses of nitrogen added through mineral fertilizers during initial soil preparation can stimulate nitrogen fixation by rhizosphere bacteria in the root zone of winter wheat. It’s important to note that ordinary and southern Chernozems and Chestnut soils have high fertility and contain readily available forms of nitrogen for plants (Patyka et al., 2001).

In the steppe zone of Ukraine, the use of biological nitrogen fertilizers is effective, even without simultaneous application of mineral nitrogen fertilizers. However, after growing non-nitrogen-fixing plant predecessors, the addition of nitrogen at a rate of N30-40 promotes increased nitrogen fixation. Biological nitrogen fertilizers like Rizoagrin are based on free-living nitrogen-fixing bacteria that continue to be active in the soil after wheat harvest. These bacteria not only have direct effects but also offer long-term benefits (Tsandur et al., 2001).

In global plant pest control practices, bacteria from the Bacillus thuringiensis group are widely used. The use of biological agents such as Trichodermin, when following recommended timelines and technologies, is quite effective. Promising candidates for the development of broad-spectrum bacterial agents include representatives of the genera Agrobacterium, Bacillus, Azospirillum, Pseudomonas, and others. In global practice, the Trichodermin agent, based on several species of the Trichoderma genus, is also well-known and effectively used against fungal diseases in agricultural crops. These fungi produce antibiotics and hydrolytic enzymes with antifungal and antibacterial activity (Barbakar, 2008).

One aspect of biological plant protection against fungal diseases involves the use of mycoparasites, which are parasites of second-order fungi or hyperparasites. Mycoparasites include species of the fungus Ampelomyces. Agents based on these fungi are used to combat fungal diseases. Additionally, for the control of soilborne infections, agents based on mycorrhizal fungi are applied, which have the ability to suppress pathogenic fungi (Fedorenko, 2008).

Another promising group for the development of bacterial agents includes representatives of the genus Pseudomonas (e.g., Ps. Fluorescens, Ps. Putida, Ps. Cerasi), which produce siderophores. Agents based on Pseudomonas bacteria (such as Ryzoplan and others) are recommended for use on neutral and alkaline soils (Nadkernychnyi et al., 1999).

Today, the importance of a scientific approach and research in modern agriculture and plant cultivation has been emphasized. Innovative technologies and production methods have become key factors in increasing crop yields, improving product quality, and enhancing production efficiency in these fields.

Field and laboratory research, along with mathematical data analysis and modeling, play a crucial role in the development of agricultural crops and the optimization of production processes. They enable the determination of optimal combinations of technological operations, forecasting yields, efficient resource utilization, and the resolution of many other tasks.

Simplifying complex processes like the cultivation of agricultural crops can be achieved through a scientific approach and the use of modern technologies. Such an approach helps make agriculture more productive, resource-efficient, and environmentally friendly.

Understanding the properties of production processes and their interactions with various factors is a crucial prerequisite for the development of modern agriculture and the attainment of high results in crop production.

The current state of agricultural production highlights the importance of agronomic research in supporting and improving the cultivation of agricultural crops. The development and refinement of methods and approaches to increase the intensity of production processes are crucial for achieving high yields and ensuring the stability and quality of agricultural products.

Furthermore, agronomic research helps reduce anthropogenic pressure on agroecosystems, including the reduction of chemical fertilizer and pesticide use, as well as optimizing water use and energy consumption. All of these measures aim to create more resilient, efficient, and environmentally friendly systems for growing agricultural crops that align with modern sustainable development requirements and ensure food security.

Therefore, the importance of theoretical research, methodological aspects, and the practical implementation of scientific research in agronomy and agriculture cannot be overemphasized. Considering various natural-climatic conditions and resources in different regions, the development and implementation of biologized cultivation technologies for agricultural crops, such as winter wheat, is a critical task to ensure the sustainability and productivity of the agricultural sector.

Achieving this goal involves working on the differentiation and adaptation of agricultural practices to specific climatic and soil conditions in various regions. Additionally, minimizing chemical impact on the environment and resource conservation requires the development and adoption of biological and environmentally friendly methods for soil treatment, plant protection, and fertilization. It is also essential to address these issues at the level of individual farms, as climatic and soil conditions can vary significantly even within small areas.

MATERIALS AND METHODS

During the period of 2017–2020, field studies were conducted. The Institute of Agriculture of the Black Sea Region of the National Academy of Agrarian Sciences of Ukraine is an important center for scientific research in the field of agricultural practices and technologies, so these studies were carried out on its research fields in the Odesa region. The context and location of the research help to understand the conditions and factors that were considered during the experiments.

When developing experimental schemes aimed at determining the effectiveness of using biological fertilizers, plant protection products, and growth regulators, information and results published in scientific publications were taken into account. This approach allowed us to use accumulated scientific knowledge and information to properly justify our research and ensure their scientific validity. Incorporating data from publications was beneficial for accurately determining optimal doses and methods of resource application, as well as for achieving the research objectives (Tsandur et al., 2001).

In the conducted experiments, a fourfold replication was used. The area of the sown plots was 86.4 m^2, and the area of the control plots was 52.8 m^2. It was used the three-factor field experiment, the scheme of which is presented below, the influence of factors such as predecessors, the use of mineral fertilizers, and the application of chemical and biological plant protection products on the yield of winter wheat variety "Knopa" was studied.

Experiment 1. Evaluation of the impact of predecessors, mineral nutrition level, pre-sowing seed treatment, and the application of biological and chemical agents on the yield of winter wheat under the conditions of the Southern Steppe of Ukraine:

1. Predecessor (Factor A):
1.1. Bare fallow.
1.2. Pea.
2. Fertilization (Factor B):
2.1. Without fertilizers (control).
2.2. Calculated dose of potassium (K).
2.3. Calculated dose of mineral fertilizers (NPK).
3. Seed treatment before sowing (Factor C):
3.1. Without treatment.
3.2. Rizoagrin, FMB, Planriz.
3.3. Vitavax 200FF.

The calculation of the required amount of potassium and total mineral fertilizer for each type of predecessor was based on agrochemical analysis and averaged as follows for the years of the research: for bare fallow – K_{79}, $N_{54}P_{79}K_{79}$; for pea – K_{59}, $N_{40}P_{59}K_{59}$. The application of mineral fertilizers with calculated doses on the research plots was done as a pre-sowing treatment.

As for seed inoculation, it was carried out immediately before sowing using a complex of biological agents such as Rizoagrin, FMB, Planriz, as well as the fungicidal seed treatment Vitavax 200FF.

The field studies, placement of experimental plots in natural conditions, and soil sampling for fertility analysis were conducted according to recognized and widely used methodologies (Horodii et al., 1972).

The stand density of winter wheat was determined through two counts during the growing season on permanent plots. Accounting plots for density determination were marked with small stakes, and the observations were conducted as follows: the first count was carried out at the stage of full emergence, and the second one – before harvesting the crop.

Phenological observations of the development of winter wheat plants included determining the onset of key growth and developmental phases of the plants, such as sowing, emergence, appearance of the third leaf, tillering, heading, flag leaf emergence, flowering stages, milk ripeness, wax ripeness, and full grain ripeness, as well as the moment of harvest (Ushkarenko et al., 1988).

RESULTS AND DISCUSSION

Previous research on the effectiveness of biologized technology for growing grain crops, including winter wheat, has confirmed that to achieve high yields at the level of 6.0–7.0 tons per hectare with the corresponding product quality not lower than grade 1–2, it is critically important to adhere to one of the key aspects of this technology – protecting crops from diseases and, at the end of the growing season (from the grain formation stage onwards), also from pests, especially the shield bug. Therefore, it is necessary to carry out at least two foliar comprehensive plant protection treatments, which include nitrogen fertilizers and insecticides.

In this research on the development of modern wheat cultivation technologies with elements of biologization, have been maintained the same background for all variants. Specifically, at different stages of plant growth, such as “early tillering” and “flag leaf formation,” we applied treatments with Bayleton and Tilt, respectively. In the “heading” and “milk ripeness” stages, winter wheat plants were treated with a complex foliar mixture, which included urea and the insecticide B-58.

During the years of our research from 2017 to 2020, favorable weather conditions prevailed. The distribution of precipitation during various growth stages of winter wheat was almost even, allowing for a high average grain yield of 6.87 tons per hectare.

However, yield variability was noticeable due to varying meteorological conditions in the years of the study. Yields ranged from 4.54 tons per hectare in 2019 (in variants with peas as the predecessor, without the application of mineral fertilizers, and without seed treatment with chemical and biological agents) to 8.89 tons per hectare in the favorable year 2020 when winter wheat was sown after fallow, the calculated doses of nitrogen, phosphorus, and potassium fertilizers were applied, and seed treatment with a complex of biological agents like Rhizoagrin, FMB, and Planriz was carried out. The difference between the minimum and maximum grain yield of winter wheat was 1.9 times.

Averaged over the years of the study, the highest grain yield, which amounted to 8.02 tons per hectare, was obtained through the cultivation of wheat after fallow, with the application of the calculated dose of mineral fertilizers ($N_{54}P_{79}K_{79}$), and comprehensive seed treatment with biological agents such as Rhizoagrin, FMB, and Planriz. The minimum yield, which was 5.0 tons per hectare, was recorded in variants with peas as the predecessor, without the application of mineral fertilizers, and without seed treatment with either chemical or biological agents. The difference between these two variants was 1.6 times.

The use of fallow as a predecessor allowed for improved soil moisture conditions and the application of more mineral fertilizers, resulting in an average yield of 7.38 tons per hectare. When wheat was grown after peas, plant productivity significantly decreased to 6.40 tons per hectare, representing a 15.3% deviation (Table 1).

Table 1. Grain Yield of Winter Wheat Depending on Primary Fertilization, Predecessor, and Seed Treatment before Sowing (t/ha)

Predecessor (Factor A)	**Fertilization (Factor B)**	**Seed treatment before sowing (Factor C)**				**Average by factors**	
		Without treatment	**Rizoagrin, FMB, Planriz**	**Vitavax 200FF**	**Average**	**A**	**B**
Bare fallow	no fertilizer	5.53	6.32	6.49	6.11	7.01	6.09
	K_{79}	6.97	7.68	7.35	7.33		6.86
	$N_{54}P_{79}K_{79}$	7.12	8.02	7.64	7.59		7.17
Pea	no fertilizer	5.00	6.51	6.67	6.06	6.40	—
	K_{59}	5.43	7.00	6.73	6.39		
	$N_{40}P_{59}K_{59}$	5.86	7.37	7.03	6.75		
Average by Factor C		5.99	7.15	6.99	—		
LSD05 Partial Differences, t/ha for Factors: A – 0.23; B – 0.19; C – 0.19							
LSD05 Average (Main) Effects, t/ha for Factors: A – 0.16; B – 0.09; C – 0.09							

As a result of the application of mineral fertilizers during pre-sowing cultivation we can observe a positive impact on the yield of winter wheat. Compared to the control variant without fertilizers, the yield increased by 0.31–1.09 tons per hectare or by 4.6–17.9%. The highest grain yield, which amounted to 7.17 tons per hectare, was achieved in variants with the application of the full dose of mineral fertilizers (NPK), compared to the variant where only potassium fertilizer was used, which resulted in a lower yield of 6.86 tons per hectare. It is important to note that the increase in yield was more significant after the predecessor "peas," where it was 5.7%, while after the predecessor "bare fallow," a slight advantage (3.5%) was observed in variants with the application of the $N_{54}P_{79}K_{79}$ fertilizer dose compared to the K_{79} dose.

The treatment of winter wheat seeds with the chemical agent Vitavax 200FF before sowing led to an increase in yield by 16.7%, reaching 6.99 tons per hectare, compared to 5.99 tons per hectare in the control variant. The maximum level of grain yield was achieved through the complex application of biological agents Rizoagrin, FMB, and Planriz, where the yield increased to 7.15 tons per hectare, which were 19.5% higher than in the control variant and 2.5% higher than in the variant with chemical seed treatment.

According to the results of the variance analysis of the experimental data, the impact of predecessors was the most important factor affecting the yield of winter wheat variety Knapa, and this factor accounted for 30.7% (Fig. 1).

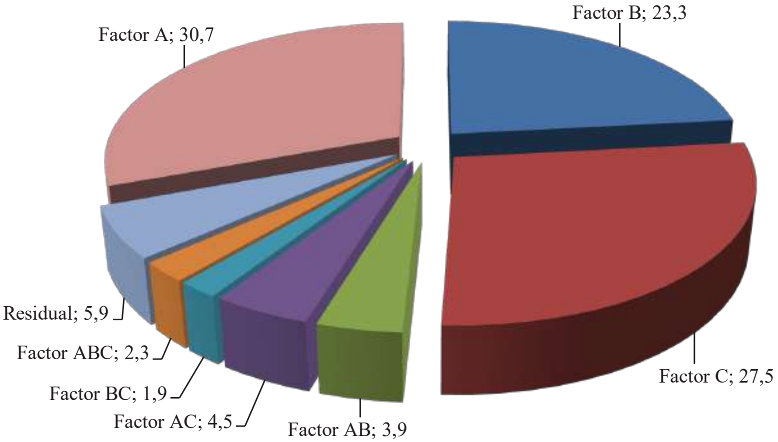

Figure 1. Share of the influence on the formation of the yield of winter wheat grain of the investigated factors, %

It is necessary to emphasize that besides the predecessors, other factors also significantly influenced the yield of winter wheat. In particular, pre-sowing seed treatment with biological agents (factor C) led to an increase in yield by 27.5% in the overall grain yield structure, while the application of fertilizers (factor B) during pre-sowing cultivation contributed to a yield increase of 23.3%. The interaction between predecessors and seed treatment (factors A and C) also had a significant impact, resulting in a 4.5% increase in yield. Minimal interaction was observed between factors B and C, leading to an increase in yield of only 1.9%. The residual effect (the influence of unaccounted factors) accounted for 5.9%, indicating the significant contribution of the studied factors and variants in shaping the yield of winter wheat.

Grain quality indicators can be divided into three groups: physical, biochemical, and technological. Physical indicators include purity, 1,000-grain weight, vitreousness, uniformity, color, and odor of the grain, among others. Purity determines the mass of a certain volume of grain (usually 1 liter). It characterizes the physical properties of the grain, such as plumpness, fullness, roughness, and hairiness. For winter wheat, purity typically ranges from 700 to 800 g/L. Purity also influences the technological qualities of the grain, and when it is less than 700 g/L, it may indicate lower flour yield. On the other hand, when purity is above 800 g/L, this trend is not observed. Reduced purity can be a warning sign of decreased wheat yield.

Another important characteristic is the 1,000-grain weight and their size. The 1000-grain weight and size are of great importance in the flour milling industry since they affect the flour yield. Based on the 1,000-grain weight, wheat is divided into four groups: high weight (above 30 g), weight above average (25–30 g), average weight (22–25 g), and weight below average (less than 22 g). Typically, wheat with a high 1,000-grain weight produces lighter flour and whiter bread crumb. Vitreousness of the grain is also an important characteristic that reflects the grain quality and the relationship between “starch and protein.” According to the research results, after the “black fallow” predecessor, the vitreousness of winter wheat grain was 58.2%, and an increase to 60.1% was recorded in one of the variants. In other cases, vitreousness decreased to 56.9–58.4%. A positive impact of biological methods on grain vitreousness was also found in combination with mineral fertilizers.

It is important to note that over the years of the research, the 1,000-grain weight remained almost unchanged, and the differences between variants were only 0.3–0.5% (Fig. 2 (see p. 304), Fig. 3 (see p. 305)).

Using the graphical method, it has been confirmed that the indicators of grain nature and the weight of 1,000 grains are closely related in all research variants. After the "black fallow" preceding crop, the lowest values of these indicators were recorded in the control variant, where the nature was 801.5 g/L with a weight of 1,000 grains of 4.2 g. The maximum values were observed in the second (805.5 g/L; 42.4 g) and fourth (806.8 g/L; 41.8 g) variants, where the tested biological agents were used during unfertilized control and when only potassium fertilizers were applied at the K79 rate.

When cultivating winter wheat after peas, slightly different trends were observed regarding the relationship between grain nature and the weight of 1,000 grains. The lowest values of these indicators were

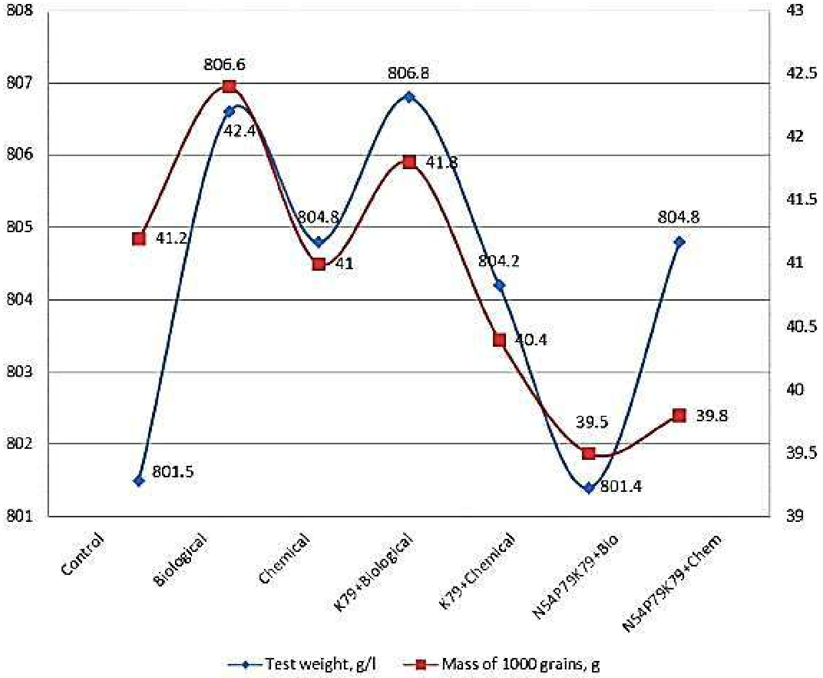

Figure 2. Dependency of the mass of 1,000 grains and test weight (bare fallow)

recorded in the control variant, where the nature was 811.1 g/L, and the weight of 1,000 grains was 42.7 g. The most significant increase in these indicators was observed in all variants of biological and chemical protection during the unfertilized control and when only potassium fertilizers (K_{59}) were applied. In variants with the combined application of nitrogen, phosphorus, and potassium fertilizers at the $N_{40}P_{59}K_{59}$ rate, some decrease in nature by 0.3–0.5% and the weight of 1,000 grains by 2.3–4.3% was noted.

For the correct calculation of the bulk weight of the grain and the determination of the grain storage capacity for further storage, relevant calculations were carried out (Patyka et al., 2003). The results of these calculations showed that after the cultivation of winter wheat after black fallow, the bulk weight of the grain was almost the same in all variants, ranging from 913 to 994 kg/m^3, while in the control variant, this indicator decreased to 847 kg/m^3,

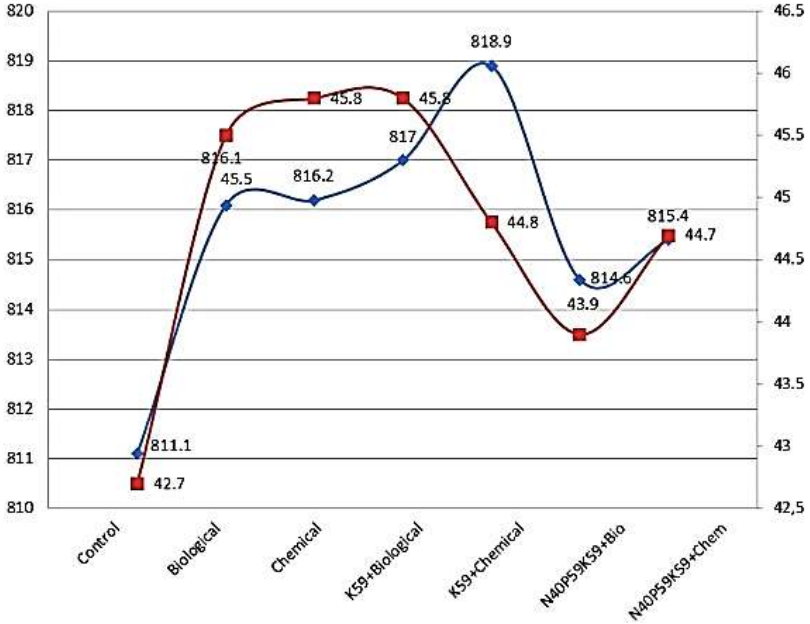

Figure 3. Dependency of the mass of 1,000 grains and test weight (pea)

or by 7.8–11.5%. After peas preceding crop in the unfertilized control, the bulk weight of the grain was 616 kg/m^3. A significant increase in this indicator was recorded in the variant with the application of full mineral fertilizer, as well as when seed inoculation with biological agents Rizoagrin, FMB, and Planriz, where the bulk weight of the grain increased to 905 kg/m^3, or by 46.9%.

The research showed that the grain quality of winter wheat in recent years in the risk zone of agriculture remains low. This is primarily explained by the low soil fertility and insufficient amounts of fertilizers for both basic application and topdressing at different stages of vegetation.

One of the important components of grain quality is protein, which is an essential organic compound, as well as gluten, which determines the quality of flour for baking needs. The protein content in grain varies from 9 to 20%, and the main part of the protein is in the endosperm.

Among many indicators characterizing the baking quality of wheat, gluten is one of the most important. The quality of gluten is determined by a combination of its physical properties, such as elasticity, extensibility, stretchability, and viscosity (Romanenko et al., 2006).

Another quality indicator for gluten is expressed in Falling Number (FN) units, which is a measure of the alpha-amylase activity in wheat flour. Falling Number is typically measured using a specific laboratory instrument called a Falling Number apparatus. It helps assess the enzymatic activity in the flour, particularly the activity of alpha-amylase, which can affect the baking quality of the flour and dough.

Higher Falling Number values indicate lower enzymatic activity, which is desirable for wheat used in bread-making. Low enzymatic activity means that starches are less likely to break down during dough processing and baking, resulting in better bread quality with good volume and texture.

On average, during three years of research, the grain quality in the unfertilized control without the use of biological or chemical agents for seed disinfection was as follows: protein content – 12.0%, gluten – 19.0%, FN – 92.7 units, and the grain was classified as third-grade food grain (Table 2).

After seed inoculation with biological agents Rizoagrin, FMB, Planriz, the average grain quality for all indicators corresponded

Table 2. Classification of winter wheat grain depending on the predecessor, fertilization, and before sowing seed treatment

Predecessor (Factor A)	**Main Fertilization (Factor B)**	**Seed Treatment Before Sowing (Factor C)**	**Grain Quality Indicators**			
			Protein, %	**gluten, %**	**FN, units**	**Grain class**
Bare fallow	no fertilizing	No Treatment	12.0	19.0	92.7	3
		Rizoagrin, FMB, Planriz	13.5	26.1	82.4	2
		Vitavax 200FF	13.2	25.9	76.9	2
	K_{79}	No Treatment	12.5	22.4	87.5	3
		Rizoagrin, FMB, Planriz	13.8	26.3	80.0	2
		Vitavax 200FF	13.0	23.5	79.5	2
	$N_{54}P_{79}K_{79}$	No Treatment	12.9	23.3	81.4	2
		Rizoagrin, FMB, Planriz	14.5	27.6	86.3	1
		Vitavax 200FF	13.7	27.1	86.9	2
Pea	no fertilizing	No Treatment	10.8	17.0	87.7	4
		Rizoagrin, FMB, Planriz	10.8	17.4	73.3	4
		Vitavax 200FF	11.7	18.4	77.4	3
	K_{59}	No Treatment	10.9	17.2	84.8	—
		Rizoagrin, FMB, Planriz	11.2	19.2	76.4	3
		Vitavax 200FF	11.7	19.1	72.2	3
	$N_{40}P_{59}K_{59}$	No Treatment	11.4	19.3	83.9	—
		Rizoagrin, FMB, Planriz	12.2	20.8	82.9	3
		Vitavax 200FF	12.0	20.1	78.3	3
LSD_{05}		Factor A	0.19	0.59	2.05	—
		Factor B	0.12	0.39	1.57	—
		Factor C	0.12	0.39	1.57	—

to the second and third grades. In the case of using only chemical technology in the unfertilized control, the grain quality increased to the second grade.

The highest grain quality indicators were achieved through biologically enhanced cultivation technology, which included the following elements:

1. Using of bare fallow as the predecessor before growing winter wheat.
2. Application of the main mineral fertilizer with doses of $N_{54}P_{79}K_{79}$ before sowing.
3. Pre-sowing seed treatment of the "Knap" variety with biological agents Rizoagrin, FMB, Planriz.

These agronomic practices allowed for the attainment of the following maximum grain quality indicators for winter wheat:

- protein content: 14.5%;
- gluten content: 27.6%;
- FN: 86.3 units;
- quality class of grain: I class.

The application of potassium with the K_{79} dose under various technologies also had a positive impact on grain quality. On average, over the years of the study, after growing winter wheat following black fallow, the grain met the quality standards of the second class, which is considered suitable for food use. After growing winter wheat following peas, the control variant yielded worse results in terms of grain quality:

- protein content: 10.8%;
- gluten content: 17.0%;
- FN: 87.7 units;
- quality class of grain: IV class.

Therefore, the use of biological agents, the correct choice of predecessor and the application of mineral fertilizers contribute to improving the quality of winter wheat grain.

CONCLUSIONS

The research conducted makes a significant contribution to understanding the factors that influence the yield and quality of winter wheat grain. Therefore, the following key general conclusions can be formulated from the obtained data:

1. Predecessor influence: The yield of winter wheat grain is significantly influenced by the predecessor. Bare fallow as a predecessor contributes to the highest yields, especially when mineral fertilizers and seed treatment with biological preparations are applied. Pea as a predecessor may lead to lower yields and grain quality, particularly without additional fertilizer application and seed treatment.
2. Fertilizer impact: The addition of mineral fertilizers, especially the calculated dose of $N_{54}P_{79}K_{79}$, has a positive impact on both yield and grain quality. Potassium fertilizers also play a crucial role in grain quality formation.
3. Biological agents: The use of biological agents such as Rizoagrin, FMB, and Planriz for seed treatment before sowing enhances grain quality, particularly increasing protein and gluten content. This primarily contributes to the grain meeting the first-class quality standards.
4. 1,000-grain weight: The 1,000-grain weight also depends on the application of biological agents and fertilizers. The use of biological preparations can lead to an increase in 1,000-grain weight, which is an important indicator for determining grain quality.
5. Growing conditions: Yield is directly proportional to various meteorological conditions. It is essential to consider this factor when planning crop cultivation.

All of these findings can be valuable for agricultural practices and research aimed at improving the cultivation of winter wheat and achieving high yields and grain quality.

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ECONOMIC EFFICIENCY OF APPLYING BIOLOGICAL GROWTH REGULATORS FOR GROWING SUNFLOWER IN THE ZONE OF STEPPE SOILS

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INTRODUCTION

Climate change is a determinant of the development of the agricultural sector of Ukraine’s economy since it affects the volume and structure of agricultural production costs (Lisetskii et al., 2016; Dudiak et al., 2019; Zhang et al., 2019; Pichura et al., 2022). Therefore, of agricultural crop varieties and hybrids adapted to climate change with advanced cultivation technologies becomes topical (USDA-ERS …, 2012;

Mateo-Sanchis et al., 2021; Skok et al., 2023). Research found that, under conditions of an increase in the air temperature, the Western and the Central Forest Steppes, Right-bank Ukraine, and Donetsk sub-zone of the Northern Steppe of Ukraine will be favorable areas for growing sunflowers (Zhigailo et al., 2016). The Steppe of Ukraine is a zone of increased risks (Nielsen et al., 2005; Domaratskiy et al., 2022).

The impact of climate change makes it necessary to improve cultivation technology (Andati et al., 2023; Liu et al., 2023). Climate change also stimulates the utilization of plant fertilization (Dobermann et al., 2022; Qiu et al., 2023) that involves foliar fertilization with macro- and micro-elements (Vinas et al., 2020; Ishfaq et al., 2022), application of plant growth regulators which enhance plant nutrition (Selanon et al., 2014; Kitano et al., 2018; Asif et al., 2022), increase the level of their stress-resistance, improve protection against unfavorable conditions of the environment, pests, and diseases (Reckling et al., 2016; Li et al., 2019; Sanford et al., 2021). Therefore, their effect can lead to an increase in the crop productivity of 5–15% (Domaratskiy et al., 2019; Korkhova et al., 2023). Therefore, the application of plant growth regulators is the most profitable method for increasing crop productivity (Singh et al., 2022; Pichura et al., 2023; Bonanomi et al., 2023). Research on the economic efficiency of applying these preparations in different climatic zones for each agricultural variety or hybrid becomes highly topical in this context.

Sunflower is a major oil-bearing crop in Ukraine, its share in the structure of crop rotations makes 25–28%. Seeds of modern released varieties and hybrids contain 50–52% of oil, and those of selected varieties and hybrids – up to 60%, therefore they require a high level of moisture content (Andrienko et al., 2020; Koutroubas et al., 2020; Jan et al., 2022). Therefore, sunflower cultivation is a priority direction in crop production (Forleo et al., 2018; Giannini et al., 2022; Petrenko et al., 2023). According to the data of the State Statistics Committee of Ukraine, crop area under sunflower cultivation in Ukraine increased sharply from 1.5 to 6.5 million hectares over the past 20 years. Forecast analysts indicate that there will be a tendency for an increase in the crop areas (Shakalij et al., 2019; Revtyo et al., 2021).

Opportunities for expanding crop areas arose after breeding the genotypes resistant to broomrape and also after implementing advanced plant protection products and herbicides (Lombardo et al., 2016; Bartucca et al., 2018; Clapp, 2021; Chen et al., 2023) that allowed removing the previous restrictions on crop areas under sunflower within 7–8% of arable lands under conditions of seven- or eight-field crop rotations (Koutroubas et al., 2020; Giannini et al., 2022). It is worth mentioning that technologies for growing sunflowers have been improved (Unakıtan et al., 2018; Galliano et al., 2018; Abdel-Rahman et al., 2019; Zhang et al., 2023), and highly productive and adaptive hybrids (Gatto et al., 2010; Dhima et al., 2012; Sher et al., 2022) capable of producing high yields under dry conditions of the Steppe zone have been bred. In particular, the average sunflower productivity in Ukraine has increased from 0.98 t/ha to 1.89 t/ha for the past 20 years (Khmarsky, 2017). However, the above high results can be improved due to the implementation of advanced production technologies based on application of eco-friendly preparations that increase the economic efficiency of crop production.

The purpose of the study is to show the economic efficiency of using eco-friendly multi-functional preparations in technological schemes for sunflower cultivation under non-irrigated conditions in the Steppe zone of Ukraine.

MATERIAL AND METHODS

Field experiments were conducted in 2021–2022 under non-irrigated conditions in the experimental field of Mykolaiv State Agricultural Research Station of the Institute of Climate-Oriented Agriculture of the National Academy of Agricultural Sciences. This research direction means conducting a three-factor field experiment identifying the impact of different biological preparations and plant density on sunflower hybrid productivity. Location of the research field and placement of sunflower hybrid crops: N 46°98'16.4'' E 32°14'57.0''. Factor A is a sunflower hybrid bred by the Plant

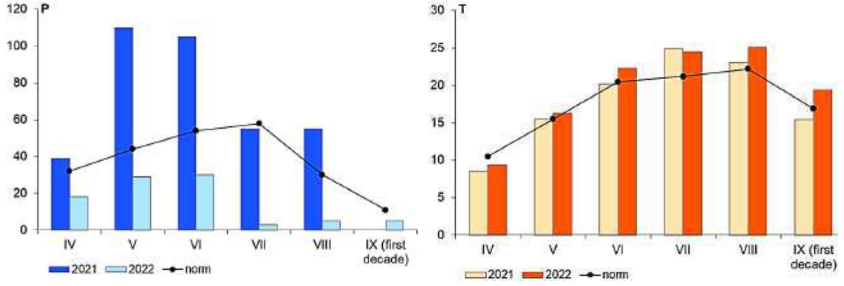
Production Institute named after V. Ya. Yuriev of the NAAS: Vyrii, Yarylo, Blysk, Yaskravyi and Epikur; Factor B – different plant densities (30, 40 and 50 thousand pcs/ha); and Factor C – plant treatment at the vegetative stage at the beginning of budding with biological preparations (Helafit Combi, Organic Balance and Biocomplex-BTU). Sunflower plants were treated with a backpack sprayer according to the research scheme. The experiment was replicated three times; the crop area of the first-order plot was 168 m^2, and the registered crop area was 120 m^2. Winter wheat was a pre-crop in the field experiment. Fertilizers were applied with basic tillage at the rate of $N_{30}P_{30}K_{30}$. The seeds were planted with row spacing of 70 cm in the last decade of April. The plant density was formed manually in each row. The soil on the experimental plots is southern black soil. The depth of a humus layer is 30 cm, and the depth of a transition layer is 60 cm. The pH of the soil solution is close to neutral (pH 6.5–6.8), and hydrolytic acidity is 2.00–2.52 mg equivalent per 100 g of soil. Availability of humus in the arable soil layer is 2.90%. Regarding mobile elements, a medium nitrogen and phosphorus and a high potassium content characterize the soil of the experimental plot. Registration of the yield and evaluation of the yield structure were erformed using manual threshing of plants selected from the registered area of the experimental plots, the seed moisture content being 8%.

The research territory is located in a continental climate zone characterized by sharp and frequent fluctuations of the air temperature, and dryness. The average annual precipitation is 360–380 mm, in spring and summer – 170 mm. Moisture accumulation in soil mainly occurs due to autumn and winter precipitation, when plants use less moisture, and evaporation is minimal. On average, the annual relative air humidity is 60–70%; in summer, it equals 40–60%. Annually, there are weak, medium, and intensive dry winds. The duration of the vegetative stage is 230–240 days.

In the research process, modeling of sunflower productivity was performed using the licensed program “Statistica 8.0”. Calculations of economic efficiency were performed based on the average prices of 2022.

RESULTS AND DISCUSSION

Research established that the level of moisture supply is a determining factor of sunflower hybrid in the conditions of the Steppe of Ukraine. Climatic conditions of 2021–2022 compared to the average multi-year indexes (norm – 1970–2020) are given in Fig. 1.



a *b*

Figure 1. Climatic conditions of the vegetative stage of sunflower cultivation, 2021–2022:
a – amount of precipitation (*P*, mm);
b – average monthly air temperature (*T*, °C)

Analysis of the soil moisture shows that the soil moisture conditions of spring 2021 (Fig. 1, *a*) were favorable for sunflower growth. A decline in air temperature and precipitation was observed in the first half of the vegetative stage. Soil moisture reserves in the arable soil layer were favorable and sufficient for crop cultivation. Soil moisture was 34 mm in the arable layer and 134 mm in a meter soil layer. Sufficient moisture content in the topsoil due to productive rainfall and moderate air temperature at the end of May created favorable conditions for sowing and even the emergence of sunflower seedlings. However, the level of moisture supply in 2022 was insufficient, which caused a moisture deficit at the critical stages of crop growth. For instance, in the entire period of sunflower hybrid growth in 2022 there was 90 mm of rainfall, which was only 39% of the average multi-year norm, its uneven distribution.

The conditions of spring 2022 were characterized by drought. On March 28, 2022, productive moisture reserves in the arable and a meter soil layer were sufficient: the arable soil layer – 39 mm, a meter soil layer – 115 mm. The pre-sowing period was characterized by dry winds that considerably reduced soil moisture. Moisture deficit at the end of May (the amount of precipitation in this period equaled 29 mm, being 66% of the norm) had a negative impact on sunflower growth and development.

The air temperature at the vegetative stage of sunflower growth in 2022 (Fig. 1, *b*) was high compared to the average multi-year indexes of each month. An increase in the air temperature against a background of soil and air moisture deficit created difficult conditions for the main phenological stages of crop development and the formation of agrocenosis productivity. Hot weather and rainfall deficit in July accelerated the phenological stages of the sunflowers. High air temperatures, low humidity, and a lack of precipitation determined an intensive soil moisture loss because of transpiration and evaporation. Dry winds in the first half of the vegetative stage of sunflower development caused a turgor loss in plats in the daytime; its restoration occurred only at nighttime.

The results of the field experiments revealed that foliar fertilization with different biological preparations is an effective and efficient method for improving conditions of plant development, which are capable of increasing the level of realization of agrocenosis genetic potential on the whole (Table 1).

Analysis of the research results for 2021 shows that a reduction in the pre-harvesting sunflower plant density from 50 thousand pcs/ha to 30 thousand pcs/ha is not appropriate (it concerns all the examined hybrids) under conditions of sufficient moisture content. The difference in sunflower productivity of different hybrids under the plant density of 40 and 50 thousand pcs/ha is not considerable. Under drought conditions in 2022, the highest productivity was observed under the plant density of 40 thousand pcs/ha. The highest level of productivity was identified in the hybrids Blysk and Vyrii.

Table 1. Sunflower hybrid productivity depending on plant density and biological preparations in 2021 and 2022, t/ha

Preparations (C)	**Hybrid (A)**									
	Blysk		**Vyrii**		**Yarylo**		**Epikur**		**Yaskravyi**	
	2021	**2022**	**2021**	**2022**	**2021**	**2022**	**2021**	**2022**	**2021**	**2022**
Plant density – 30 thousand pcs/ha (B)										
Control (without treatment)	2.43	1.74	2.84	1.83	1.73	1.58	1.66	1.51	1.71	1.63
Helafit Combi	2.79	1.88	3.38	2.05	1.89	1.66	1.76	1.68	1.93	1.81
Organic Balance	2.71	1.80	3.07	1.99	1.91	1.70	2.01	1.61	2.09	1.78
Biocomplex-BTU	2.68	1.81	3.31	1.94	1.88	1.69	1.93	1.63	2.00	1.77
Plant density – 40 thousand pcs/ha (B)										
Control (without treatment)	2.57	1.92	2.92	2.01	1.74	1.81	1.69	1.74	1.85	1.77
Helafit Combi	2.98	2.11	3.51	2.22	1.95	1.95	1.90	1.91	2.03	1.85
Organic Balance	2.99	2.09	3.55	2.19	2.06	1.94	1.97	1.88	1.99	1.84
Biocomplex-BTU	2.83	2.10	3.48	2.16	2.01	1.88	2.04	1.80	2.06	1.79
Plant density – 50 thousand pcs/ha (B)										
Control (without treatment)	2.63	1.77	3.00	1.85	1.83	1.55	1.70	1.58	1.88	1.70
Helafit Combi	3.07	1.84	3.61	1.92	2.01	1.64	2.02	1.63	2.13	1.81
Organic Balance	3.02	1.80	3.54	1.88	2.03	1.65	2.11	1.64	2.15	1.76
Biocomplex-BTU	3.04	1.81	3.60	1.90	1.99	1.60	2.08	1.63	2.09	1.75
LSD$_{05}$, t/ha (ABC)	0.07	0.05	0.09	0.06	0.07	0.06	0.09	0.07	0.08	0.06

The research results prove that the treatment of vegetating plants with biological preparations positively affected the formation of productivity of the examined agrocenoses. In 2021, the highest productivity of 3.61 t/ha was registered in the hybrid Vyrii with the plant density of 50 thousand pcs/ha and plant treatment with Helafit Combi. The productivity was 3.60 t/ha with the plant density of 50 thousand pcs/ha plant treatment with Biocomplex-BTU. In 2022, the hybrid Vyrii had the highest productivity of 2.22 t/ha with the plant density of 40 thousand pcs/ha and plant treatment with Helafit Combi.

The results of the two-year research prove that the yields of the hybrids Yarylo, Epikur, and Yaskravy were lower yields than those of the hybrids Blysk and Vyrii. It is worth mentioning that foliar fertilization with biological preparations applied to the hybrids with lower productivity also positively affected their yields. A low level of productivity in 2021 (1.66 t/ha) was characteristic of the hybrid Epikur with the plant density of 30 thousand pcs/ha; in 2022, this hybrid productivity equaled 1.51 t/ha with the same plant density. Low productivity in 2022 was observed in the hybrid Yarylo (1.5 t/ha) with the plant density of 50 thousand pcs/ha.

Economic analysis of the research results was performed based on the prices in Ukraine at the beginning of October 2022 (the price of 1 t of sunflower seeds was $325 (including VAT)). To perform analysis, production costs were calculated according to the flow process charts based on the pre-harvesting plant density and treatment with biological preparations (Table 2–4, see p. 318–321).

Table 2. Economic efficiency of sunflower hybrid cultivation depends on biological preparations under conditions of the pre-harvesting density of 30 thousand pcs/ha (prices in 2022)

№	**Variant of the experiment**	**Yield, t/ha**	**Production costs, $/ha**	**Operating profit, $/ha**	**Cost price, $/t**	**Profitability, %**
1	**2**	**3**	**4**	**5**	**6**	**7**
Blysk						
1	Control (without treatment)	1.74	565.00	0.50	324.70	0.09
2	Helafit Combi	1.88	571.25	39.75	303.85	6.95
3	Organic Balance	1.80	571.25	13.75	317.35	2.40
4	Biocomplex-BTU	1.81	571.25	17.00	315.60	3.00
Vyrii						
1	Control (without treatment)	1.83	565.00	29.75	308.75	5.26
2	Helafit Combi	2.05	571.25	95.00	278.65	16.63
3	Organic Balance	1.99	571.25	75.50	287.05	13.22
4	Biocomplex-BTU	1.94	571.25	59.25	294.45	10.37

End of Table 2

1	2	3	4	5	6	7
Yarylo						
1	Control (without treatment)	1.58	565.00	−51.50	357.60	−9.11
2	Helafit Combi	1.66	571.25	−31.75	344.13	−5.56
3	Organic Balance	1.70	571.25	−18.75	336.03	−3.28
4	Biocomplex-BTU	1.69	571.25	−22.00	338.03	−3.85
Epikur						
1	Control (without treatment)	1.51	565.00	−74.25	374.15	−13.14
2	Helafit Combi	1.68	571.25	−25.25	340.03	−4.42
3	Organic Balance	1.61	571.25	−48.00	354.80	−8.40
4	Biocomplex-BTU	1.63	571.25	−41.50	350.45	−7.26
Yaskravyi						
1	Control (without treatment)	1.63	565.00	−35.25	346.63	−6.20
2	Helafit Combi	1.81	571.25	17.00	315.60	2.98
3	Organic Balance	1.78	571.25	7.25	320.93	1.27
4	Biocomplex-BTU	1.77	571.25	4.00	322.73	0.70

Table 3. Economic efficiency of sunflower hybrid cultivation depends on biological preparations under conditions of the pre-harvesting density of 40 thousand pcs/ha (prices in 2022)

№	Variant of the experiment	Yield, t/ha	Production costs, $/ha	Operating profit, $/ha	Cost price, $/t	Profitability, %
1	2	3	4	5	6	7
Blysk						
1	Control (without treatment)	1.92	568.25	55.75	295.95	9.81
2	Helafit Combi	2.11	574.50	111.25	272.28	19.36
3	Organic Balance	2.09	574.50	104.75	274.88	18.23
4	Biocomplex-BTU	2.10	574.50	108.00	273.56	18.80
Vyrii						
1	Control (without treatment)	2.01	568.25	85.00	282.70	14.96
2	Helafit Combi	2.22	574.50	147.00	258.78	25.59
3	Organic Balance	2.19	574.50	137.25	262.33	23.89
4	Biocomplex-BTU	2.16	574.50	127.50	265.98	22.19

End of Table 3

1	2	3	4	5	6	7
Yarylo						
1	Control (without treatment)	1.81	568.25	20.00	313.95	3.52
2	Helafit Combi	1.95	574.50	59.25	294.63	10.31
3	Organic Balance	1.94	574.50	56.00	296.13	9.75
4	Biocomplex-BTU	1.88	574.50	36.50	305.58	6.35
Epikur						
1	Control (without treatment)	1.74	568.25	−2.75	326.58	−0.50
2	Helafit Combi	1.91	574.50	46.25	300.78	8.15
3	Organic Balance	1.88	574.50	36.50	305.58	6.35
4	Biocomplex-BTU	1.80	574.50	10.5	319.18	1.83
Yaskravyi						
1	Control (without treatment)	1.77	568.25	7.00	321.05	1.23
2	Helafit Combi	1.85	574.50	26.75	310.55	4.66
3	Organic Balance	1.84	574.50	23.50	312.23	4.10
4	Biocomplex-BTU	1.79	574.50	7.25	320.95	1.26

Table 4. The economic efficiency of sunflower hybrid cultivation depends on biological practices under the pre-harvesting density of 50 thousand pcs/ha. (prices in 2022)

№	**Variant of the experiment**	**Yield, t/ha**	**Production costs, $/ha**	**Operating profit, $/ha**	**Cost price, $/t**	**Profitability, %**
1	**2**	**3**	**4**	**5**	**6**	**7**
Blysk						
1	Control (without treatment)	1.77	571.50	3.75	322.88	0.66
2	Helafit Combi	1.84	577.75	20.25	314.00	3.50
3	Organic Balance	1.80	577.75	7.25	320.98	1.25
4	Biocomplex-BTU	1.81	577.75	10.50	319.20	1.82
Vyrii						
1	Control (without treatment)	1.85	571.50	29.75	308.93	5.20
2	Helafit Combi	1.92	577.75	46.25	300.90	8.00
3	Organic Balance	1.88	577.75	28.25	307.30	4.89
4	Biocomplex-BTU	1.90	577.75	39.75	304.08	6.88

End of Table 4

1	2	3	4	5	6	7
Yarylo						
1	Control (without treatment)	1.55	571.50	−67.75	368.70	−0.12
2	Helafit Combi	1.64	577.75	−44.75	352.28	−7.74
3	Organic Balance	1.65	577.75	−41.50	350.15	−7.18
4	Biocomplex-BTU	1.60	577.75	−57.75	361.10	−10.00
Epikur						
1	Control (without treatment)	1.58	571.50	−58.00	361.70	−10.15
2	Helafit Combi	1.63	577.75	−48.00	354.45	−8.31
3	Organic Balance	1.64	577.75	−44.75	352.28	−7.74
4	Biocomplex-BTU	1.63	577.75	−48.00	354.45	−8.31
Yaskravyi						
1	Control (without treatment)	1.70	571.50	−19.00	336.18	−3.32
2	Helafit Combi	1.81	577.75	10.50	319.20	1.81
3	Organic Balance	1.76	577.75	−5.75	328.28	−0.99
4	Biocomplex-BTU	1.75	577.75	−9.00	330.15	−1.56

Production costs in all the variants of the experiments were identical and equaled $565/ha. However, the difference was determined by the cost of additional treatment with biological preparations ($6.25/ha), and the cost of seeds increased by approximately $3.25/ha because of a rise in the seeding rate by 10 thousand pcs/ha calculated per hectare. It was established that foliar fertilization with biological preparations applied to different sunflower hybrids under conditions of different sowing densities positively impacted plant development and increased crop productivity. On the whole, cultivation of the hybrids Blysk and Vyrii had the highest indexes of the level of profitability in comparison with the hybrids Yarylo, Epikur, and Yaskravyi. An increase in the pre-harvesting plant density in 2022 to 50 thousand pcs/ha caused unprofitability in growing the hybrids Yarylo, Epikur, and Yaskravyi. The level of unprofitability (−10.15%) was registered in the control variant of the hybrid Epikur with the plant density of 50 thousand pcs/ha.

Cultivation of the sunflower hybrids Blysk and Vyrii with the plant density of 40 thousand pcs/ha under conditions of plant treatment with biological preparations was profitable. The highest level of profitability (25.59%) and net profit ($127.20/ha) was reached in the variant of the hybrid Vyrii with the plant density of 40 thousand pcs/ha and plant treatment with the preparation Helafit Combi. It is worth mentioning that a decline in sunflower production efficiency in 2022 is related to a fall in productivity caused by dry weather, a drop in purchase prices 1.5 times, and an increase in the prices for plant protection products, fuels and lubricants, and replacement parts.

CONCLUSIONS

The field experiments conducted in 2021 and 2022 allowed for establishing the efficiency of applying eco-friendly plant growth regulators for growing sunflower hybrids. The experiments make it possible to draw the following conclusions:

1. Droughts characterized the conditions of spring 2022. There was 90 mm of precipitation in the entire period of sunflower hybrid growth in 2022, which was only 39% of the average multi-year norm. The rainfall distribution was uneven, and that had a negative impact on crop productivity.
2. The research results of 2022 showed that all the hybrids had the highest productivity under the plant density of 40 thousand pcs/ha. Crop density at 50 thousand pcs/ha had lower yields than those in the variants with the plant density of 40 thousand pcs/ha and were almost identical to those with the plant density of 30 thousand pcs/ha. The highest productivity in the years of the research was observed in the hybrids Blysk and Vyrii.
3. Biological preparations had a positive impact on agrocenose productivity. The highest productivity of 2.22 t/ha in 2022 was characteristic of the hybrid Vyrii in the variant of plant treatment with Helafit Combi and the plant density of 40 thousand pcs/ha. The hybrids Yarylo, Epikur, and Yaskravy had a considerably lower level of productivity. However, foliar fertilization also had a positive effect and contributed to an increase in their productivity. A low level of productivity in 2022 (1.51 t/ha) was observed in the hybrid Epikur under the plant density of 30 thousand pcs/ha.

4. Plant foliar fertilization with biological preparations under conditions of different sowing densities improved sunflower productivity, proving their positive impact on the economic efficiency of crop production. A high level of profitability was characteristic of the hybrids Blysk and Vyrii, with a plant density of 40 thousand pcs/ha and plant treatment with biological preparations. The highest level of profitability (25.59%) and the maximum net profit ($127.20/ha) was reached when growing the sunflower hybrid Vyrii with the plant density of 40 thousand pcs/ha and plant treatment with the biological preparation Helafit Combi.

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A CONCEPTUAL FRAMEWORK FOR THE ENVIRONMENTAL AND ECONOMIC SECURITY OF AGRARIAN NATURAL RESOURCE MANAGEMENT

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INTRODUCTION

Global food production has increased by some 300% over the past 50 years, thanks to humanity's incredible capacity for innovation. However, the world continues to lose more than a third of all food produced, with annual losses exceeding $900 billion. The global market for smart agriculture has been estimated at $15.3 billion in 2020 and is expected to reach $22.5 billion by 2026. According to recent estimates, global demand for food will increase dramatically by 70% by 2050, requiring an investment in agriculture of around $80 billion to feed a projected nine billion people (EOS Crop Monitoring…, 2020).

Due to population growth, significant demand for agricultural products is driving up the cost of fertilizers, pesticides, herbicides, and other agricultural inputs. In addition, global warming provokes severe droughts and soil degradation. All this makes agriculture critical to the sustainable development of humankind. Broadly speaking, agricultural technology is designed to increase farm productivity and profitability by reducing costs or crop losses.

In many countries around the world, national agricultural policies do not distinguish between land and water use in the context of food security as a separate priority. The problem is the relevance of putting environmental and economic stewardship into practice. The issue of safe drinking water supply and sanitation overlaps with such issues.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Thus, the world increasingly recognizes that complex, multifaceted issues, such as food security and nutrition, require holistic, cross-sectoral approaches, pooling of resources from different countries, innovation, and knowledge for stakeholders. Instruments are in place and FAO by 2030 suggests strengthening global partnerships; fostering innovation; implementing international projects; government programs; civil society development in the aspect of environmental management (Agroecological and other innov …, 2019; National Economic Strategy …, 2021; Skrypchuk et al., 2020; Geo-management in organic agricu …, 2019).

DISCUSSION

Therefore, the implementation of a coherent public policy aimed at the European and Euro-Atlantic course, building relations with new Asian and Middle Eastern centres of gravity, creating a favourable business climate, developing entrepreneurship and export support, attracting investment, and developing capital markets, developing domestic consumption and other mechanisms will strengthen the country’s position as a regional actor and become projects for economic growth. Ensuring the implementation of innovative projects for faster economic growth will contribute to the development of the state's economy through the appropriate quality of education, science, medicine, culture, and environmental conservation (EPC) in the context of a green economy. Transformed and organized agrarian business projects and environmentally and economically sound environmental management systems will be able to effectively provide a competitive advantage in the international market for goods and services with foreign countries, which will contribute to increased tax revenues to the budget and income of the population. Hence the tasks of formation of ecological and economic security of agrarian nature management are: to search for ways of reforming the Ukrainian economy into a socially responsible, ecologically safe, economically expedient one, which requires implementation of ecologization, digitalization, socialization, and economic justification through the system of different management levels from global to small and individual level (human as nature user, as a community resident, outlined by certain territory); implementation of mechanisms of intellectualization (Fig. 1).

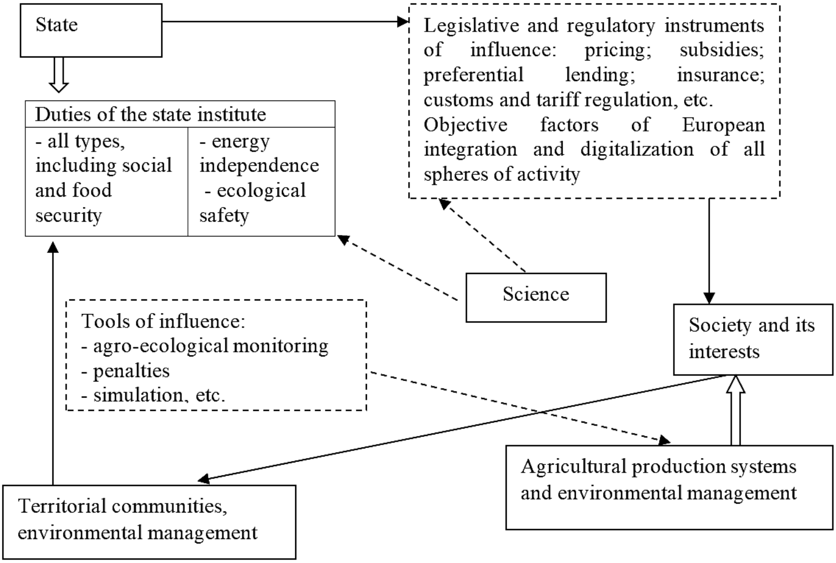

Figure 1. Place of ecological and economic security of agrarian nature use in the life of the state

The safety of agrarian natural resource use should be considered as a tool for ensuring the environmental safety of the sphere as a whole of all types of natural resource use for the general public of users of the natural environment; practical tools for regulating environmental and economic relations at both macro and micro levels; a system of criteria for macroeconomic assessment of natural resources (from the state to the community level), namely, it takes into account the peculiarities of reproduction and systematic management of the natural environment, tools for various types of management, etc.

The formation of agrarian environmental security should be carried out at the global, regional, local, and point levels. The local level should be studied so that its indicators serve as initial data for assessing security only at the regional level. It is necessary to consider many different indicators (sanitary and toxicological, ecological, sociological, demographic, medical, etc.) in order to quantify the safety of agrarian environmental use of the territory (community).

The development of conceptual provisions for environmental safety in agrarian environmental use is based on the principles of prevention and compensation for damage caused by the natural environment. This includes the program of adapting Ukrainian legislation to comply with the standards of the European Union, as well as Ukraine’s candidacy for EU membership.

Environmental safety encompasses a set of conditions, processes, and actions that maintain ecological balance in the natural environment, preventing any significant damage or threats to both the environment and human beings. It also involves protecting the vital interests of individuals, society, nature, the state, and humanity as a whole from real or potential threats arising from human-made or natural impacts on the environment.

Barriers to achieving environmental safety of agrarian environmental management:

- war in Ukraine;
- unreasonable tax system;
- the threat of growing state budget deficit (need to increase state expenditures on environmental management;

- low level of lending (insufficient protection of lenders' rights);
- an inefficient system of registrations, permits, and licenses (excessive bureaucratic burden on business, lack of digitalization of procedures);
- burdensome state supervision (pressure on business by regulatory authorities);
- lack of a comprehensive strategy to promote a competition on the part of the state;
- insufficient level of intellectual property rights protection;
- incomplete harmonization of Ukrainian legislation with EU legislation (harmonization in the areas of security, environmental protection, green economy, etc.);
- an imperfect system of protection of the rights of communities, farmers, and population, regarding the quality of the natural environment, and its use in the future;
- low level of environmental and economic literacy.

The purpose of establishing a framework for the security of agrarian environmental management is to systematically consider the state of the natural environment and its potential as a vital component of economic, environmental, and social security for individual territories (e.g., communities). This involves providing theoretical, methodological, and practical socio-ecological and economic support to ensure the security of agrarian environmental management.

Additionally, the goal is to optimize the utilization of water and land resources (e.g., water and land footprints), assess the environmental risks associated with energy plants in different regions, and explore the use of energy crops for the future.

Hence, a comprehensive environmental assessment of the safety of agrarian environmental use of the territory of communities, regions, etc. should include:

- systematic assessment of the complex factors of the natural environment, and social sphere;
- determination of anthropogenic load;
- zoning of the territory in terms of tasks and relevant indicators (through the environmental audit procedure);

- identification of factors, resources, and sequence of works for economic activities based on the principles of a "green" economy;
- continuous monitoring (GIS, etc.), for example regulation of impacts on the natural environment; control of sources of impact on the natural environment; quality control of natural environment components;
- management decision-making: formation of socio-ecological and economic decisions;
- development and improvement of environmental legislation and methods of environmental outlook formation.

The conceptual framework for the agrarian environmental security formation defines the following principles and values in the socio-ecological and economic spheres of state activity:

- direction of movement ("key benchmarks") – European integration (implementation of the strategic course of the state for Ukraine's full membership in the EU);
- decarbonization of the economy (increasing energy efficiency, developing renewable energy sources, developing a circular economy, and synchronization with the European Green Deal initiative);
- effective digital service state and compact state institutions (development of the digital agricultural economy as one of the drivers of Ukraine's economic growth);
- the rule of law (inviolable private property, observance of the rule of law in the implementation of the state environmental policy in the field of all types of environmental management);
- development of "green" entrepreneurship, innovation, and digitalization (Delivering the European Green Deal…, 2019);
- institutional capacity ("a state capable of ensuring development");
- pragmatism, subjectivity in determining the directions of economic development;
- systemic economic approach, the ability to effectively combine the needs and real capabilities of the natural environment;
- implementation of the European Green Deal, including the achievement of climate neutrality by 2050.

Agroecological principles are used to implement the principles of agrarian environmental security formation:

1. Increasing the efficiency of resource use:
   - recycling. Preference for the use of local renewable resources and closing, as far as possible, the resource cycles of nutrients and biomass;
   - reducing the use of production resources. Reducing or eliminating dependence on purchased inputs and increasing self-sufficiency.
2. Strengthening resilience to external factors:
   - soil health. Ensuring and improving the health and functions of the soil to improve plant growth, especially through the rational organization of organic matter and increasing the biological activity of the soil;
   - animal health. Ensuring the health and welfare of animals;
   - biodiversity. Maintaining and increasing the diversity of genetic resources at the farm and landscape scale;
   - synergism. Improving positive ecological interactions, synergies, complexity, and complementarity of agroecosystem components (forests, soils, and water);
   - diversification of economic activities. Diversification of incomes generated in the farming sector, by ensuring greater financial independence of small farmers and opportunities to improve the depth of processing, while allowing to meet consumer demand.

To ensure the application of agrarian environmental security principles, it is crucial to introduce innovations in various fields such as environmental management, auditing, expertise, insurance, licensing, information and environmental economics, metrology, standardization, certification, and project management. Specifically, there is a need to establish a regulatory and legal framework that defines the scope of activities, products, natural environment facilities, and territories subject to auditing and voluntary environmental certification.

The mechanism for ensuring the environmental safety of a territory (communities) follows a systematic sequence of scientific and practical research. Its primary objective is to establish reliable and reasonable criteria while identifying effective measures to enhance the environmental condition of the natural surroundings.

The first stage encompasses defining quantitative indicators and criteria for environmental safety, evaluating adverse events, and determining the structure, system, and quantitative assessment of territorial safety.

The second stage involves assessing the methods and mechanisms for ensuring territorial safety, as well as implementing this system into the practical management of districts (communities).

The implementation of environmental safety for the territory (communities) will be carried out through the following means:

- the principles of the formation of agrarian environmental security will be used as the basis for preparing draft programs, strategic documents, and draft laws;
- measures to achieve the strategic goals and relevant objectives of the state economic policy will be incorporated into the action plans of the Cabinet of Ministers of Ukraine and the relevant plans of ministries;
- the current strategic documents of the Cabinet of Ministers of Ukraine, activity plans of ministries, and other central executive bodies will be reviewed and adjusted to align with the principles of agrarian environmental security.

The implementation of the principles of agrarian environmental security is anticipated to occur in three stages.

In the first stage, the priority tasks should be the formation of the legislative and regulatory framework; development of a strategy for the implementation of provisions; improvement of the integrated environmental management system, interagency coordination, and cooperation on the integration of the environmental component into the development programs of economic sectors; ensuring the development and approval of regional development strategies in conjunction with and by the requirements of environmental management; preparation of a regulatory framework for environmental audit procedures and possible environmental impact assessment.

The second stage envisages organizational, marketing, and training work in the field of environmental management, audit, insurance, certification, and provision of consulting services for organizations of all forms of ownership.

In the third stage, it is planned to conduct audit procedures (environmental audits) and certification of objects and territories of communities according to the priorities of innovation and investment development; systematization of all information, and, the creation of data banks, including commercial ones.

The types of work involved in the implementation of the principles of agrarian environmental management security include:

1. Identification of adverse impacts on the natural environment: The primary objective of this stage is to identify and compile a comprehensive list of events and activities that lead to the deterioration of the natural environment's quality.

2. Assessment of facts and events involves systematically evaluating adverse impacts that may be classified as risky or crisis within a specific period and in a given territory. Various methods of adverse event assessment are distinguished, including:

- statistical assessment, based on the analysis of accumulated statistical data;
- analytical assessment, based on the study of cause-and-effect relationships within the system, this method allows for a comprehensive evaluation of adverse events as complex phenomena;
- expert, that provides assessment of possible consequences by processing the results of expert surveys.

3. The determination of the structure of agrarian nature management aims to organize nature use in a manner that minimizes damage to the natural environment and protects public health. The guiding principle is rational nature management, which advocates for maintaining a balance between human activities and ecosystem capacities.

4. Quantitative safety assessment involves conducting studies with the purpose of developing numerical indicators to evaluate

agrarian environmental safety. These assessments may involve various methodologies, such as integral assessments, expert evaluations, modeling techniques, and utilization of digital data available online.

5. The decision-making process regarding the introduction and control of agrarian environmental safety management practices involves a comprehensive conformity assessment. This assessment includes evaluating the compatibility and alignment of these practices, including environmental certifications if applicable, with the most optimal types of agrarian environmental management.

Control over the results of individual stages of safety assessment is conducted through various means related to the monitoring of the state of the natural environment, audit of existing facilities, licensing of activities, inspections, and other relevant processes.

The introduction of an effective system of audit and certification (including environmental) at different levels should be implemented through:

1. The administrative reform aims to implement a series of measures to enhance the efficiency and effectiveness of environmental management. These measures include:

- development of legislative and regulatory framework: the reform involves creating a comprehensive legislative and regulatory framework that considers international conventions, agreements, and emerging areas of standardization, certification, and accreditation amidst globalization and intense competition;
- improvement of the list of products and services subject to mandatory or voluntary certification, including the requirements of environmental standards, creation of environmentally certified products, facilities, and territories of the natural environment register;
- development of methods that legislatively fix the schemes, methods of audit and certification and, accordingly, accreditation of conformity assessment bodies;
- revision, clarification, delimitation of functions of rights and duties of central and regional bodies of state and executive power on the regulation of complex environmental activities in the territories of different levels;

- reduction of administrative interference in the production and economic activities of market economy entities by stimulating the introduction of safe agricultural pyro use;
- theoretical and methodological coordination of certification importance as the final link in the system of state environmental and economic control;
- introduction of electronic services, elimination of corruption risks in the judicial system, improvement of the general business climate, simplification of the registration system, obtaining permits and licenses, simplification of tax administration.

2. Reforming the tax and financial sector through:

- conducting financial, credit, and tax policy in the direction of creating an optimal system of taxation and benefits for both business entities and administrative entities;
- reforming the mechanism of financing environmental protection measures to benefit business entities and initiate the introduction of environmentally friendly management methods;
- a creation of a crediting system for local authorities, production enterprises, organizations to stimulate the introduction of environmentally safe environmental management in general (green business and tourism technologies, socially oriented business, etc.);
- granting the right to local (regional) authorities to accumulate funds for solving environmental issues in the amount of up to (60–90)% at the expense of violators of environmental legislation;
- to provide in the Tax Code annual depreciation rates at the level of 20% and 50% for equipment intended for research and metrological support of the natural environment audit and monitoring procedure;
- introduction of profit tax discounts in the amount of 30% for enterprises operating in the certified territory;
- introduction of interest-free, low-interest loans for audit and certification;
- differentiation of prices for raw materials and products produced in certified areas, first of all for agricultural products (organic, ecological raw materials and products), and later for services in the field of tourism, recreation, etc.

3. Transformation of investment activity, which includes:

- introduction of special regimes, and investment activities in certified areas (including ecologically);
- stimulation of leasing and concession activities in certified areas in order to consolidate the status and appropriate quality of the natural environment;
- a creation of specially certified zones (territories) in environmentally balanced projects (dietary and organic food, etc.).

4. Improvement of the organizational and economic mechanism for the establishment of the audit and certification system, which includes (Fig. 2, see p. 340):

- development of environmental certification formation methodology (including environmental);
- monitoring existing and developing new draft laws, recommendations, regulations, instructions, including departmental ones;
- establishing a state system of assurances and incentives, achieved through an organizational and economic mechanism to facilitate certification (including environmental certification) of products, services, and the sustainability of agricultural landscapes and territories;
- transforming the payment distribution mechanism between various levels of budgets;
- creating regional environmental insurance systems aimed at accumulating funds to finance audit and certification procedures, including those related to environmental standards;
- setting up specialized scientific, consulting, and other organizations to conduct audits, certification, etc.

Creation of institutional conditions. The main goal of such reform should be to create a decentralized model of natural environment management capable of effectively influencing the processes of socio-economic development of territories:

- the creation of institutional infrastructure (a central certification body within the structure of the Ministry of Ecology and Natural Resources of Ukraine and independent environmental auditors who have been trained and have the appropriate license, or a certified commercial structure);

- training in order to obtain the appropriate license;
- expanding financial and economic opportunities of territorial communities, strengthening the motivation of local governments to strengthen local budgets;
- instruments of public-private partnership, methodological approaches to the valuation of the natural environment (natural capital) of Ukraine, in particular:
  - administrative and legal instruments, namely: the legislative and regulatory framework (laws and resolutions of the Cabinet of Ministers of Ukraine, directives, and regulations of international organizations) and norms (standards of different types, industries, and countries, limits, quotas, etc.);

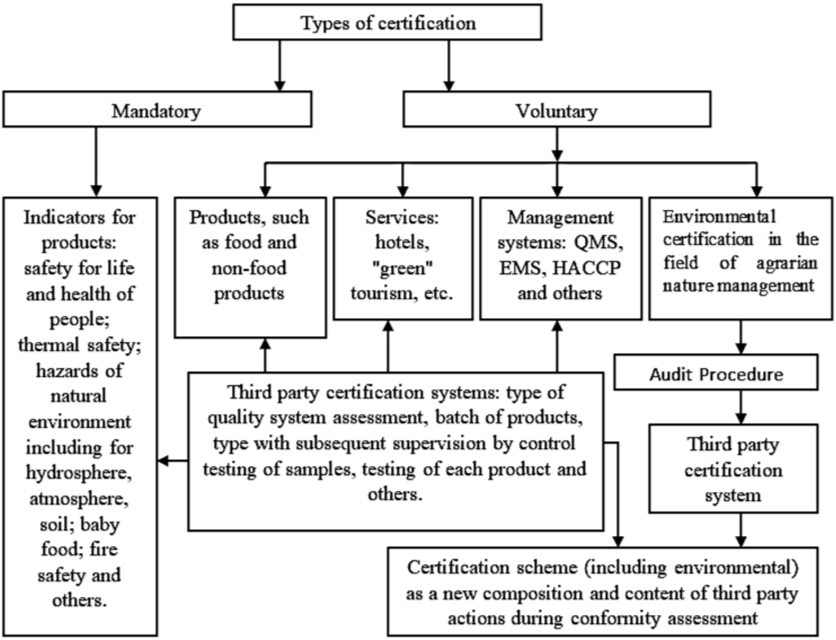

Figure 2. Methodological approaches to improving the system and certification scheme in Ukraine and the world as a tool for the implementation of environmental safety of territories

– economic instruments: subsidies, grants, loans, leasing, insurance, payments for environmental use, pricing instruments, preferential taxation, etc.;

– communication and information support, education, public participation, multi-level monitoring of the environmental sphere, environmental engineering, consulting.

Legislative and regulatory support consists of:

▪ amendments to the Law of Ukraine “On Environmental Protection”, the Law of Ukraine “On the Basic Principles (Strategy) of the State Environmental Policy of Ukraine for the period up to 2030”, “On Conformity Assessment”, “On Standardization”, “On Metrology and Metrological Activities”, “On Consumer Protection”, “On Conformity Assessment”, “On Waste”, etc.;

▪ harmonization of several EU directives, for example, Directive No. 2011/92/EU on the assessment of the effects of certain public and private projects on the environment; Directive No. 2000/60/EC establishing a framework for Community action in the field of water policy, as amended; Directive No. 2008/50/EC of the European Parliament and the Council on ambient air quality and cleaner air for Europe; Directive 2003/4/EC of the European Parliament and of the Council of 28 January 2003 on freedom of access to information relating to the environment and others;

▪ development of legislative and regulatory documents that will include a set of legal provisions on certification of environmental management: development of technical regulations; preservation of mandatory certification of products and services share for the period of economic reform in order to protect consumers from counterfeit products; introduction of voluntary certification in the field of environmental management (including agricultural); continued harmonization of legislative and regulatory documents of Ukraine with international ones, etc.

The scientific and methodological support includes: legislative and regulatory documents of the ministries of Ukraine, EU, WTO, ISO; natural environment quality methodology; Total Quality Management concept; certification schemes; strategies and concepts for digitalization and greening of the economy; scientific and methodological developments of the UN, FAO; concepts in the field of agribusiness and environmental economics:

- the integration of agrarian cluster development into the overall concept of cluster formation in Ukraine;
- creation of a regulatory framework to facilitate the operational functioning of agrarian clusters;
- establishing a comprehensive system for monitoring land relations, simplifying land management regulations, and implementing digitalization measures for permitting procedures and administrative services related to land affairs;
- ensuring the establishment of a national geospatial data infrastructure, decentralizing regulatory powers of state bodies in land relations to local self-government bodies, and creating favorable legal, tax, financial credit conditions to promote the vibrant growth of agricultural cooperation and other forms of associations among small producers;
- streamlining the process of conducting economic activities for business entities involved in crafting food products for local agricultural markets;
- initiating programs aimed at supporting organic producers;
- implementation of measures to enhance producers' awareness of the advantages of organic production;
- introducing a traceability system in supply chains for agricultural resources used in production and marketing;
- establishing a fair tax burden for farms operating within the legal framework;
- testing European administrative practices in managing agricultural production entities;
- promoting the concept of "Industry 4.0" and its components as essential factors in boosting the competitiveness of industrial enterprises;
- facilitating educational initiatives to transfer IT sector best practices to various industrial sectors;
- developing new competencies for industry personnel to effectively implement digital technologies;
- facilitating clustering in the field of Industry 4.0 at both national and regional levels;

- creating conducive conditions for establishing and growing industrial parks as investment destinations with existing infrastructure;
- establishing and maintaining a geographic information system to monitor regional and territorial community development;
- promoting effective communication and collaboration among central executive authorities, local self-government bodies, the public, and businesses;
- adopting and implementing the smart specialization approach in each region, following the EU methodology;
- facilitating Ukraine's membership in the European Smart Specialization Platform (S3 Platform).

Incorporating digital technologies is vital for implementing safe agrarian environmental management principles. These technologies play a key role in achieving equilibrium in agrarian environmental management, with a particular focus on fostering sustainable food and agricultural systems. Primarily, this entails the adoption of automation technologies and alternative web platforms.

The envisioned outcome of adopting safe agrarian environmental management principles includes garnering public support for the state's strategic direction in the socio-ecological and economic realms. It will also lead to the creation of competitive conditions for agribusiness and investments, contributing to GDP per capita and labor productivity growth. Most importantly, it ensures the preservation of the natural environment's quality, safeguarding its integrity for future generations.

Positive outcomes resulting from the adoption of safe agrarian environmental management principles include:

1. Abundant availability of domestically produced food, ensuring an ample supply of high-quality products.
2. Achievement of nutritional well-being through access to a balanced diet, clean water, and proper sanitation, fulfilling all physiological requirements.
3. Promotion of stability for the state's socio-ecological and economic development.
4. Ensuring access to a pristine natural environment, characterized by high quality and ecological health.

The anticipated outcomes of introducing the ABAP as a new ideology for agrarian environmental management in Ukraine will be evident in:

- establishment of efficient environmental management systems in administrative entities and specific regions;
- adoption of a mixed (public and private) audit and certification process, operating under a third-party certification scheme;
- substantial increase in investment attractiveness due to transparent information on the state of natural resource potential;
- augmentation of revenue for all levels of budgets, driven by production growth, increased investments, and clear financial policies;
- rise in the number and business activity of enterprises engaged in environmentally oriented endeavors;
- modernization of the legislative regulatory framework governing standardization, metrology, conformity assessment, and consumer protection;
- notable progress in enhancing consumers' environmental awareness;
- attraction of investments and reduction of capital investment risks;
- vigilant product safety control for the natural environment, as well as the well-being, health, and property of Ukrainian citizens, among others.

CONCLUSIONS

As a consequence, advancements in environmental safety necessitate the implementation of Ukraine's European integration provisions related to environmental management, audit, and overall environmental certification. The tax reform in the country will play a role in stimulating audit and certification procedures in the field of environmental management, leading to expected results under the following conditions:

- ensuring macroeconomic, social, and political stability in society;
- combining state and market economic mechanisms for the rational utilization of natural capital;

- promoting transparency in economic relations, such as the introduction of a 5% purchase tax;
- reducing corruption and fostering a conscious attitude towards protecting public interests by the general public;
- efficient utilization of public funds accumulated through taxes and fees, with a focus on increasing public investment in human and natural capital.

Furthermore, the transformation of food systems into sustainable ones requires numerous measures encompassing all links of the food chain. This has been supported by studies such as those by Spaargaren et al. (2011) and Hinrichs (2014) (Spaargaren, 2011; Hinrichs, 2014). The proposed developments align with the provisions of food security and Agenda 2030 (2021), as well as the EU-Ukraine Association Agreement (2003).

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MORPHO-PHYSIOLOGICAL ADAPTATIONS OF CARP FISH TO THE ECOLOGICAL CONDITIONS OF THE HORYN RIVER

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INTRODUCTION

A significant volume of literature data has been accumulated on the study of fish morphometry. He proves that questions related to the variability of signs are convenient methodical approaches for multi-faceted research. All known studies on the variability of morphometric features of fish can be divided into the following areas: 1) study of geographical variability of species with a wide range; 2) study of variability associated with local variations in conditions; 3) study of variability associated with changes in conditions over time; 4) studying the variability of artificial groups and populations; 5) analysis of the variability of morphometric indicators when modelling living conditions.

In natural conditions on fish there are many factors that influence their metabolism and growth, that is, there is a complex effect of inanimate phenomena mediated by biotic factors.

For example, it has been proven that temperature determines the rate of metabolic reactions (a controlling factor) and complicates the processes of internal regulation (a masking factor). Changes in lighting affect the functioning of the endocrine system (a driving factor), while factors such as oxygen content, body weight, and diet can restrain growth (a limiting factor).

In most of the works on the study of the influence of hydrochemical factors on the growth rates of fish, there are data that prove the determining importance of pollution associated with human activity. Of course, both in natural conditions and in the experiment, a decrease in growth rates is observed with deviations from the normal chemical composition of water (Ledebur et al., 1973).

Causes of decrease in the rate of growth of fish at deterioration of quality of water, as a rule, are found: a decrease in the amount of available food, a deterioration in the appetite of fish, a decrease in feeding activity and the ability to find and capture prey, a decrease in the efficiency of food utilization and the ability to properly digest and assimilate it (Lukyanenko, 1983).

Research on two hydrologically identical sections of the Pilitsa River (Penczak, 1976), which experience varying degrees of exposure to household pollution, revealed a significant lag in the growth of weeds from the polluted section. Early ripening and suppression of the growth rate of whitefish (*Coregonus lavaretus* (Linnaeus, 1758)) were observed in the water bodies of the Kola Peninsula, which experienced aerotechnological pollution from a nickel production plant. A slowdown in the growth rate of juveniles (weighing 5–13 g) of rainbow trout (*Parasalmo mykiss* (Walbaum, 1792)) was observed when they were kept in soft acidified (pH 5.2) water with a sublethal dose of aluminium (38 mg/dm^3) (Wison et al., 1994).

Some works prove that not always a decrease in the rate of growth of one or another type of fish is a consequence of deterioration of values of hydrochemical parameters of water. An example of this could be an unexpected reaction of fish to acidification of the oligotrophic lakes of southern Finland, among which have separated a group of highly acidic (6 lakes from $pH < 5$), moderately acidified (5 lakes from $pH < 6$) and neutral (5 lakes from $pH > 6$). It turned out that among the 16 studied reservoirs, the rate of growth of river perch (*Perca fluviatilis* (Linnaeus, 1758)) in the lakes of the first two groups was higher (Australian and New Zealand guidelines for fresh …, 2000). A similar situation was observed in the same reservoirs, where the water became more acidic. Four years after acidification of the lakes (pH decreased to 4.7–4.8), an acceleration of the growth of perch was noticed (Australian and New Zealand guidelines for fresh …, 2000). The author assumes that the rate of growth accelerated due to a decrease in the number of fish (as a result of acidification) and a weakening of intra- and interspecies competition. Other studies have established that optimal conditions for fish growth correspond to water pH values above 4.5 and Al and Fe concentrations <1.0 mg/dm^3.

Interesting data were obtained when studying the effect of toxic pollution of the Caspian Sea hydroecosystem on the biochemical and morphophysiological disorders of the kutum (*Rutilus frisii kutum* (Kamensky, 1901)) and the round goby (*Gobius cephalarges* (Pallas, 1814)). Thus, at relatively low concentrations of oil (0.05–1.0 mg/dm^3), changes in growth processes were adaptive: growth accelerated at certain stages, and slowed down during chronic exposure. At high concentrations of oil (from 40 mg/dm^3 and above), the growth of fish significantly slowed down and even stopped (400, 800 mg/dm^3) (Kurbanova, 2022). The Chukuchan population (Catostomus commersoni (Lacepède, 1803)) at increased concentrations of zinc and copper due to atmospheric deposition showed increased growth rates and fecundity, while the fish reached sexual maturity earlier. Ore waters, which contained the same concentrations of these elements, caused a slowdown in growth, reduced fertility, but the maturation period of individuals remained the same (Australian water quality guidelines for fresh …, 1992).

A rather interesting picture of the dynamics of changes in fish growth over time depending on different concentrations of toxicants was obtained during a model experiment: the value of the specific growth rate of young guppies (*Poecelia reticulata* (Peters, 1859)) in aquariums with a Cu^{2+} concentration of 0.1 mg/dm^3 decreased for the second week up to 30%, on the third week it increased by almost 50%, and on the fourth week it again decreased by 20%.

In aquariums with a concentration of the toxicant of 0.001 mg/dm^3 and in the control, fluctuations in the values of the specific growth rate were observed: at the beginning of the experiment, the specific growth rate increased noticeably, then sharply decreased and again rapidly increased. In the presence of Cd^{2+} in different concentrations in aquariums, no significant changes in the body weight of fish were observed. However, the study of the changes in the dynamics of the specific growth rate of fish gave the authors of the experiment a reason to claim that in aquariums with the highest concentration of Cd^{2+}, the value of this indicator constantly decreases, while at the lowest concentration and in the control it increases sharply (Ashfak, 1999).

The influence of carbon dioxide (CO_2) in the water exerts a fairly significant influence on the growth and vital activity of fish, but even here it is possible to observe different strength and directionality of the influence of this factor. Thus, chronic exposure to elevated CO_2 levels was correlated with lower growth indices of many fish species, which differed from the growth rates of fish under normal carbon dioxide concentrations by 21 to 58%.

In particular, this summer flounder (*Pleuronectes platessa* (Linnaeus, 1758)) kept in water with different concentrations of dissolved carbon dioxide: ~3,000, 15,000, 25,000 μatm (respectively, 5, 26 and 42 mg/dm^3), with increasing CO_2 decreased feed consumption against the background of activation of protein catabolism (Stiller et al., 2015). Apparently, as in the case of high acidity, fish can adapt to the influence of chemical factors after a certain time. In addition, under the influence of “chemical stress”, fish reduce their spontaneous motor activity and, as a result, most of the energy can be used for growth.

There are known data on the effect of various chemicals on the individual variability of fish sizes. When water is saturated with

NO_2 in concentrations from 15 to 130 mg/dm^3, growth inhibition of *Danio rerio* (Hamilton, 1822) was noted on the 28th day of keeping fish in an aquatic environment, starting with a nitrogen dioxin concentration of 73 mg/dm^3, with an exponential relationship between the growth rate of fish and NO_2 concentration, with the value of approximation $R^2 = 0.896$ (Biedunkova, 2010).

It has been proven on the basis of considerable experimental material that the specific growth rate of young fish is a highly sensitive biological production parameter to the presence of such toxicants as hexavalent chromium, nickel, and lead in water. There are also interesting data on the reaction of morphometric indicators of fish to the action of pesticides. The analysis of the influence of various drugs revealed reliable changes in the rates of linear and weight growth of experimental prelarvae *Huso huso* × *Acipenser ruthenus*. Thus, dimoxystrobin in concentrations of 0.0005 mg/dm^3 and 0.001 mg/dm^3 caused a decrease in the rate of weight growth, while linear growth did not change. Fluoxastrobin at a concentration of 0.1 mg/dm^3 caused a statistically significant decrease in the rates of linear and weight growth of the experimental organisms. In solutions of dimoxystrobin with a concentration of 0.0001 mg/dm^3, trifloxystrobin and pyroclostrobin with a concentration of 0.0005 mg/dm^3, fluoxostrobin at 0.01 mg/dm^3 and 0.05 mg/dm^3, no deviations from the norm were observed in all studied parameters in prelarvae of the *Huso huso* × *Acipenser ruthenus*.

A comparison of the total concentrations and discharge volumes of pollutants in the wastewater of Dniprovazmash Open Joint Stock Company with the morphometry and biomass of juvenile fish of the coastal communities of the Dnipro Reservoir in 2007–2011 revealed a direct relationship between these indicators. The calculated correlation coefficients for these values confirm a strong positive relationship between the given parameters: the correlation coefficient is 0.62 (coefficient of determination 38.4%), for the mass of pollutants and ichthyofauna biomass – 0.92 (84.6%) (Bobilyov et al., 2013).

Radiation as a factor affecting fish growth can act directly or through changes in fish life cycles. For example, long-term observations of carp kept in the cooling pond of the Chernobyl nuclear power plant showed that silver carp (*Hypophthalmichthis molitrix* (Valenciennes, 1844)) after irradiation began to mature at much smaller sizes than individuals from normal populations. When modeling group and individual variability of morphometric characteristics of river fish under the influence of radionuclides (^{3}H, ^{14}C, ^{60}Co, ^{134}Cs, ^{137}Cs, ^{65}Zn, ^{89}Sr, ^{90}Sr, ^{125}I, ^{131}I, etc.), it was observed that these parameters largely depend on abiotic factors such as volumetric flows and water temperature (Smith, 2006).

At the same time, it was noticed that the factors that act within the framework of "local variations" often may not lead to significant changes in the morphometric characteristics of fish. Abiotic and biotic factors affect fish at the same time, and the negative effect of one factor can often be compensated by the positive effect of another (Demchenko, 2012).

So, in the analyzed literature, there is clearly a strong opinion that the variability of morphometric features of fish is one of the most indicative and sensitive characteristics of the influence of environmental factors on ecosystems. Therefore, we can generalize that the study of morphometric variability of fish is a justified approach that makes it possible to describe and control changes in hydroecosystems, provided that assessments are carried out in clearly defined local conditions.

MATERIALS AND METHODS

The study of the ecological and morphophysiological characteristics of representatives of the carp family was carried out in the section of the Horyn River in the northern part of the Rivne region of Ukraine.

The Horyn River is the right tributary of the Pripyat River. It originates on the Volyn-Podilsk plateau in the Ternopil region, flows through the territory of the Khmelnytskyi and Rivne regions. The total length of the river is 659 km, it has 40 tributaries. The channel is moderately winding, the river belongs to the plain type. The total catchment area is 27,700 km^{2}. In the regime, there is a well-defined flood, there are no borders, which are disturbed by summer and winter floods from rains and showers. The intra-annual distribution of the flow of the Horyn River is uneven in years with different water levels: on average, spring accounts for 50–70%, summer – 10–15%, and winter 15–30% of the annual flow, the annual flow rate is 5.98 m^3/s. The river is mainly fed by snow and rain with a significant contribution of groundwater. In the middle and lower reaches of the basin, significant areas are covered by peatlands.

The water and hydrochemical regime of the river is significantly influenced by underground and karst waters of the marl-chalk layer, which bring calcium and magnesium hydrocarbonates to the river. The amount of mineralization in the riverbed reaches 562–620 mg/dm^3, its decrease is observed along the course of the river.

Fish catches were carried out during the summer-autumn season of 2021 years, using fishing rods and lures. In addition, during the collection of material, the catches of fishermen were recorded.

Control catches of fish were carried out in two reservoirs located in the northern part of the Rivne region: site № 1 – the Vysotsk village, Dubrovytskyi district, below the discharge of domestic wastewater treatment facilities in the Dubrovytsia city; site № 2 – below Smorodsk village within on the border with Belarus (Fig. 1, see p. 353).

Processing of the obtained material was carried out according to generally accepted ichthyological methods. Body weight and 8 linear features were determined in each individual: full length – the distance from the beginning of the snout to the vertical end of the largest blade of the tail fin (ab), mm; short length – the distance from the beginning of the snout to the beginning of the middle rays of the caudal fin (ad), mm; Smith length – the distance from the beginning of the snout to the fork of the tail fin (ac), mm; head length – lateral distance from the beginning of the snout to the rear and most distant end of the gill cover without the gill membrane (ao), mm; the greatest height of the fish’s body – the vertical distance from the highest point of the body to the abdomen (gh), mm; the smallest height of the fish body – tail stem (ez), mm; eye length (np), mm; eye height (rs), mm (Fig. 2, see p. 353).

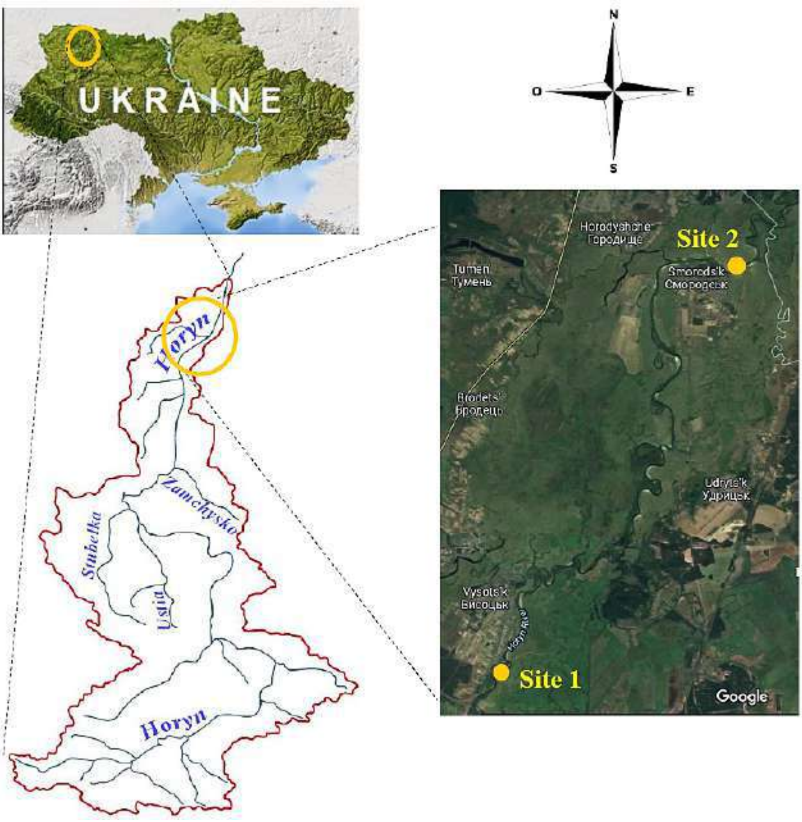

Figure 1. Placement of fish control sites

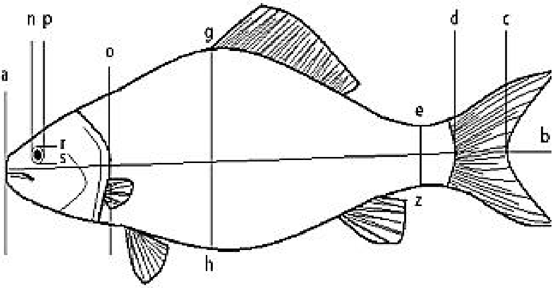

Figure 2. Scheme of measurements of fish

The obtained results were subjected to mathematical and statistical processing to establish the coefficient of variation, which allows judging the variability of morphometric features. For this, a number of formulas were used:

$$M = \frac{\sum x}{n}, \tag{1}$$

where M – arithmetic mean; x – is the amount of the option; n – is the number (quantity) of measurements, or the size of the sample.

Standard error of the arithmetic mean (m):

$$m = \pm \frac{\delta}{\sqrt{n-1}}, \tag{2}$$

where σ – root mean square deviation.

Mean square deviation (σ):

$$\delta = \pm \frac{\sqrt{\sum (x - M)^2}}{n-1}, \tag{3}$$

where x – options; M – arithmetic mean.

Coefficient of variation (C_v):

$$C_V = \frac{\delta \times 100\%}{M}, \tag{4}$$

where σ – arithmetic mean deviation; M – arithmetic mean.

If $C_v < 5$ – the variability of the sign is insignificant; $C_v = 5$–10 – the variability of the sign is average; $C_v > 10$ – the variability of the sign is high.

The coefficient of fatness was determined as the ratio of mass to body length according to the formulas of Fulton and Clark, which take into account the weight of the fish, the weight of the viscera, and the length of the body to the end of the scaly cover:

- according to T. Fulton:

$$K_f = \frac{P \times 100}{l^3}; \tag{5}$$

- according to F. Clark:

$$K_f = \frac{(P - p) \times 100}{l^3}, \tag{6}$$

where *P* – weight of fish, g; *p* – a mass of viscera, g; *L* – body length to the end of the scaly cover, cm.

The dynamics of changes in fish growth were determined by the distances between annual rings of fish scales, using a microscope (Fig. 3, *a*).

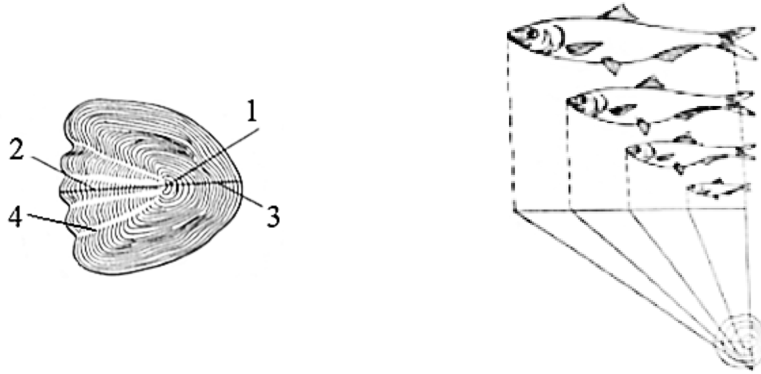

Figure 3. *a* – Scheme of the structure and appearance of the cycloid scale of bony fish:

1 – the centre of the scale; 2 – front radius of the scale; 3 – posterior radius of the scale; 4 – power channels; *b* – Correlation of the size of the fish body to the distance between the annual rings on the scales

In order to avoid misinterpretation of the age of fish, a clear rule was followed when conducting assessments: the zone of closely spaced sclerites is located immediately behind the zone of widely spaced sclerites, and the outer boundary of the zone of closely spaced sclerites is taken as the annual ring.

The reverse calculation of fish growth (Fig. 3, *b*) was carried out according to the formula:

$$\frac{l_n}{l} = \frac{V_n}{V} \rightarrow l_n = \frac{V_n \times l}{V}, \tag{7}$$

where l – the length of the fish at the time of capture, mm; V – the length of the scales along the middle line from the centre to the edge, mm; *ln* – the calculated length of the fish at the age of n years, mm; *Vn* – the distance from the centre of the scale to the annual ring at the age of n years, mm.

To assess the morphological homeostasis of fish, 9 bilateral meristic features of fish were used: the number of rays in the pectoral (*P*) and ventral fins (*V*); number of gill stamens on the first gill arch (sp. br.); the number of petals in the gill membrane (f. br.); the number of scales in the lateral line (jj); the number of scales with sensory tubules (jj. sk); the number of rows of scales above (squ. 1) and below (squ. 2) the lateral line; the number of scales on the side of the caudal fin (squ. pl) (Fig. 4, see p. 357) (Zakharov, 1993).

The level of fluctuating asymmetry was assessed according to the integral indicator of the frequency of asymmetric manifestation of FAM (Zakharov, 1987):

$$FAM = \frac{\sum_{i=1}^{k} A_i}{n \times k}, \tag{8}$$

where *FAM* – number of asymmetric manifestations; A_i – the number of asymmetric manifestations of trait *i* (the number of individuals asymmetric by trait); *n* – sample size; *k* is the number of features.

Morphological homeostasis, formed during the early ontogenesis of fish, was determined by the average frequency of asymmetric manifestation of the trait (FAMT).

The quality of the water environment was judged according to the established indicators of FAM and FAMT: less than 0.30 – 1 point, the quality of the environment is “conditionally normal”; 0.3–0.34 – 2 points, “initial (minor) deviations from the norm”; 0.35–0.39 – 3 points, “average level of deviations from the norm”; 0.40–0.44 – 4 points, “significant (significant) deviations from the norm”; more than 0.45 – 5 points, “critical condition”.

In the course of our research, we analyzed 1 scale from each individual of both fish species, which was taken between the lateral line and the dorsal fin. When examined under a microscope, the number of annual rings and the distance between them were counted. For the accuracy of measurements, we used Horyaev’s counting camera and fixed the number of pixels in 1 mm using the software package “Adobe Photoshop”.

To get an idea of the ecological state of the surface waters of the Horyn River, in which representatives of carp live, we used the hydrochemical monitoring data of the Rivne Ecological Inspectorate, which were evaluated using the Methodology (Romanenko et al., 1998).

The methodology includes the assessment of hydrochemical parameters of water according to three blocks of indicators: the block

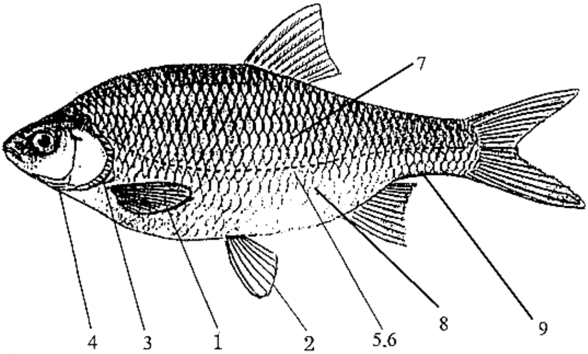

Figure 4. Scheme of meristic features of fishes for assessment of developmental stability:

1 – the number of rays in the pectoral fins (*P*); 2 – number of rays of abdominal fins (*V*); 3 – number of gill stamens on the first gill arch (sp. br.); 4 – the number of petals in the gill membrane (f. br.); 5 – the number of scales in the lateral line (jj); 6 – the number of scales with sensory tubules (jj. sk); 7 – the number of rows of scales above the lateral line (squ. 1)

of saline composition (I_1), the block of tropho-saprobiological (sanitary and hygienic) composition (I_2) and the block of specific toxic substances (I_3). On the basis of uniform ecological criteria, the method allows to compare the quality of water in separate areas of water bodies and in water bodies of different regions and consists in calculating the integral index of water quality (I_e) according to the formula:

$$I_e = \frac{I_1 + I_2 + I_3}{3} \; . \qquad (9)$$

The obtained values of block and integral ecological indices, according to the ecological classification, were compared with the following quality state of water: excellent state 1.0–1.4 (standard of comparisons); transitional from excellent to good 1.5–1.6; good 1.7–3.4; transitional from good to satisfactory 3.5–3.6; satisfactory 3.7–5.4; transitional from satisfactory to poor 5.5–5.6; bad 5.7–6.4; transitional from bad to very bad 6.5–6.6; very bad 6.7–7.0.

RESULTS AND DISCUSSION

Cyprinidae are an extremely diverse group of fish. Representatives of the family are distinguished by the shape of the body, the structure and number of pharyngeal teeth, the shape and placement of fins. Some of them live only in cold, well-oxygenated waters, but many fish prefer warm waters with low oxygen content. Carp fish do not migrate long distances. Females lay a large number of eggs and after fertilization do not show any concern for them. Among the carp, there are many species that do not reach significant sizes, so they are not of industrial importance.

Linear weight characteristics of ichthyological samples of representatives of the Cyprinidae family

Common carp (*Cyprinus carpio* Linnaeus, 1758) is a common freshwater fish of the carp family. For Ukraine, this is an alien species originating from Asia. Carps naturalized in “wild” reservoirs have certain external differences from “pond” forms of carp.

The results of our determinations of linear weight characteristics of carp individuals (Table 1) show that the average weight of individuals in the sample was 287.74 ± 72.75 g.

Table 1. Linear weight characteristics of the analyzed individuals of *C. carpio* (n = 38)

Statistical parameters*	Size and weight characteristics of fish								
	Body weight, g	Full length, mm	Body length according to Smith, mm	Small length, mm	Eye length, mm	Eye height, mm	Head length, mm	The greatest height of the body, mm	The smallest height of the body, mm
M	287.63	200.86	180.08	170.53	9.68	10.08	48.76	62.39	23.89
±m	48.89	14.19	13.04	12.91	0.34	0.37	3.76	4.36	2.05
min	11.0	111.0	91.00	84.00	7.00	7.00	21.00	27.00	9.00
max	942.0	389.0	356.00	346.00	14.00	15.00	96.00	117.00	52.00
δ	301.36	87.53	80.38	79.56	2.11	2.26	23.17	26.88	12.61
C_v	104.77	43.57	44.63	46.65	21.88	22.41	26.88	43.09	52.79

*M – arithmetic mean; ±m – standard error of the arithmetic mean; min – the minimum value of the characteristic in the sample; max – the maximum value of the characteristic in the sample; δ – mean square deviation; C_v – coefficient of variation.

The average values of the full length of individuals were at the level of 200.86 ± 14.19 mm length according to Smith – 180.08 ± 13.04 mm, average values of small length – 170.53 ± 12.91 mm, eye length – 9.68 ± 0.34 mm, eye height – 10.08 ± 0.37 mm, head length – 48.76 ± 3.76 mm, average values of the largest body height of fish – 62.39 ± 4.36 mm, smallest body height – 23.89 ± 2.05 mm.

Silver crucian carp (*Carassius gibelio*) is sometimes considered a subspecies of Chinese crucian carp (*Carassius auratus gibelio*). Morphologically, it is very similar to common crucian carp, but differs in a dark abdominal shell and large teeth on the last unbranched rays of the dorsal and anal fins, which do not reach the base of the fin. Life expectancy up to 12 years.

They live in rivers, ponds, lakes, ditches. Undemanding to water quality, it can live in very muddy water bodies with low oxygen content in the water, even in swamps. They can submerge in silt and tolerate short-term drying of the reservoir, and remain alive when the reservoir freezes. Omnivorous fish, feeds on algae, detritus, plankton, and invertebrates. In winter, they sink into the mud, where they remain motionless until the ice melts. In some reservoirs of southern Ukraine, they do not stop feeding actively all winter under the ice cover.

The results of our determinations of linear weight characteristics of silver crucian carp caught in the Horyn River (Table 2) showed that the average weight of individuals in the sample was 92.63 ± 17.08 g.

The average values of the full length of the individuals were at the level of 164.61 ± 9.66 mm, the Smith length – 149.82 ± 6.86 mm, the average values of the small length – 138.86 ± 6.56 mm, the eye length – 8.45 ± 0.22 mm, eye height – 8.43 ± 0.16 mm, head

Table 2. Linear weight characteristics of the analyzed individuals of *C. gibelio* (n = 57)

Statistical parameters*	**Size and weight characteristics of fish**								
	Body weight, g	**Full length, mm**	**Body length according to Smith, mm**	**Small length, mm**	**Eye length, mm**	**Eye height, mm**	**Head length, mm**	**The greatest height of the body, mm**	**The smallest height of the body, mm**
M	92.94	164.61	149.82	138.86	8.45	8.43	30.66	43.26	15.47
±m	9.66	7.29	6.86	6.56	0.22	0.16	1.17	2.37	0.95
min	7.0	73.0	70.00	63.00	4.00	6.00	19.00	23.00	8.00
max	250.0	265.0	260.00	245.00	12.00	11.00	55.00	83.00	32.00
δ	72.95	55.07	51.79	49.51	1.67	1.21	8.86	17.89	7.19
C_v	78.49	33.45	34.57	35.66	19.74	14.34	28.90	41.36	47.51

*M – arithmetic mean; ±m – standard error of the arithmetic mean; min – the minimum value of the characteristic in the sample; max – the maximum value of the characteristic in the sample; δ – mean square deviation; C_v – coefficient of variation.

length – 30.20 ± 1.17 mm, average values of the largest body height of fish – 43.26 ± 2.37 mm, smallest body height – 15.47 ± 0.95 mm.

A comparison of the linear features of fish with the full length of their body clearly demonstrates the differences in the morphological structure of various types of carp (Fig. 5).

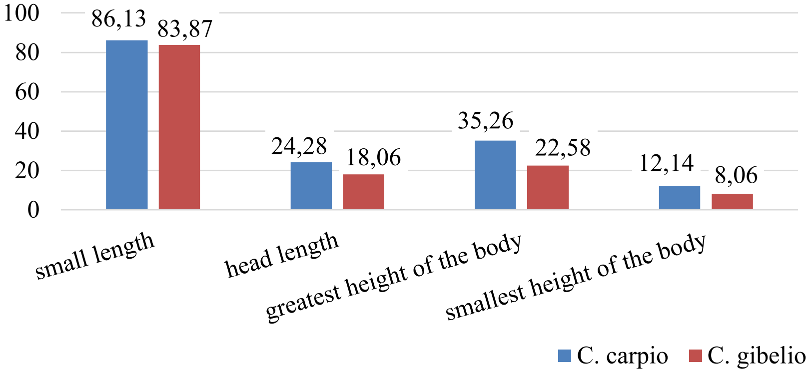

Figure 5. Specific features of the ratio of linear features to the full length of the fish body, %

Thus, the ratio of short length to full body length was slightly higher in carp and was 86.13%. In carp, this indicator was at the level of 83.87%. The ratio of the length of the head to the total length of the body of fish had a noticeably greater difference, which was 24.28% in carp, and 18.06% in crucian carp. The largest and smallest body height in relation to the total length were also greater in carp – 35.26% and 12.14%, respectively. In carp, this ratio was 22.58% and 8.06%, respectively.

Thus, the analysis of linear weight characteristics of *C. carpio* and *C. gibelio* made it possible to notice that size differentiation occurs for different species of fish belonging to the same family.

Determination of fish fattening ratio

The coefficient of fattening is an indicator that characterizes the fattening of fish.

This indicator is used in fish farming to determine the readiness of various groups of fish for wintering, that is, for the period of "hungry exchange", as well as to assess the general physiological state of fish in specific conditions of reservoirs.

A total of 6 specimens of carp and 5 specimens of silver crucian carp were analyzed. Thus, the average weight of experimental carp individuals was 253.0 ± 71.07 g, with an average weight of viscera of 14.4 ± 3.80 g and an average body length of 13.9 ± 1.38 cm. The average weight of silver crucian carp individuals was 150.6 ± 23.43 g with an average weight of viscera of 9.64 ± 1.62 g and an average body length of 16.22 ± 2.07 cm. The average values of the calculated fatness coefficients of representatives of carp were slightly higher for the examined individuals of silver crucian carp – 6.11 according to Fulton and 5.73 according to Clark. The average fatness of the examined carp individuals was 5.46 according to Fulton and 5.13 according to Clark (Fig. 6).

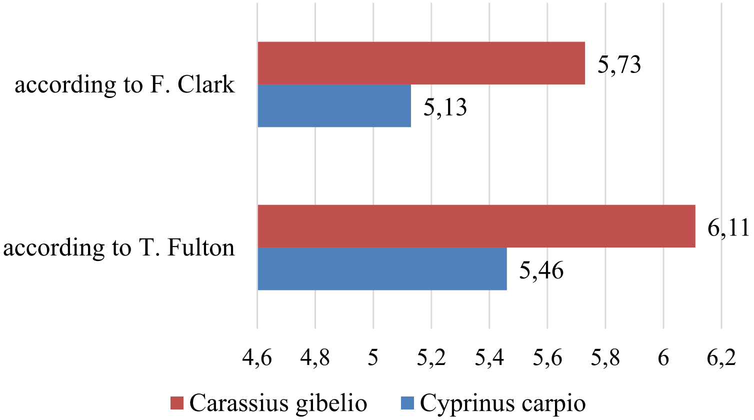

Figure 6. Comparative assessment of fatness coefficients for studied species of fish

Perhaps this is explained by the physiological characteristics of different types of fish, in particular, the terms of spawning. After all, it is known that the silver crucian carp spawns in portions, which lasts from the beginning of June to the beginning of October, depending on the temperature characteristics of the water bodies.

In general, the values of the fish fattening coefficients obtained allow us to make an assumption about the sufficient supply of the natural feed base of the analyzed fish species and their good physiological condition, because it is known that the minimum fattening coefficient of carp, which reflects their ability to winter, is 2.9 for this summer and 3.6 for two- and three-year-old individuals.

Estimation of linear sizes of fish in the process of ontogenesis

One of the absolute advantages of fish scales is its ability to record the age of a fish and to perform the function of a registration structure that allows the retrospective analysis of the growth of each individual individual. Since the scales grow almost synchronously with the fish body, it is possible to establish the nature of the relationship between the length of an individual and a certain diameter of the scales based on a sample of a separate population, and on the basis of this dependence, calculate the values of the length of the individual, which correspond to the size of the diameter of the annual ring on its scales (Fig. 7).

Cyprinus carpio *Carassius gibelio*

Figure 7. The appearance of the scales of the studied fish species at the general magnification of the microscope 8 × 40

The sample of carp was represented by individuals of age categories from one-year-old (1+) to four-year-old (4+). The average length of their scales along the middle line from the centre to the edge was 3.71 mm (Table 3, see p. 364).

The sample of crucian carp was also represented by individuals of age categories from one-year-old (1+) to four-year-old (4+). The average length of their scales along the middle line from the centre to the edge was 3.72 mm (Table 4, see p. 364).

Table 3. Reverse calculations of *C. carpio* growth in the process of ontogenesis

Age of the individual, years	The length of the scales along the middle line from the center to the edge (V, mm)	Distances from the center of the scale to the annual ring at the age of n years (Vn, mm)	The calculated length of the fish at the age of n years (ln, mm)	Dynamics of changes, %
1+	3.71	1.53	126.2	+83.28
2+		2.96	231.3	+26.20
3+		4.42	291.9	+22.20
4+		4.95	356.7	

Table 4. Reverse calculations of *C. gibelio* growth in the process of ontogenesis

Age of the individual, years	The length of the scales along the middle line from the centre to the edge (V, mm)	Distances from the centre of the scale to the annual ring at the age of n years (Vn, mm)	The calculated length of the fish at the age of n years (ln, mm)	Dynamics of changes, %
1	3.72	1.34	80.5	+96.27
2		2.85	158.0	+42.68
3		3.58	225.4	+21.11
4		3.67	273.1	

Thus, the estimated retrospective dynamics of changes in the growth of carp and silver crucian carp shows that the second year of life of individuals had more accelerated rates (+83.28% and +96.27%, respectively) compared to the third and fourth years of life. At the same time, silver crucian carp had a greater increase in body length (42.68%) in the third year of life, compared to carp in the same year of ontogenesis (26.20%).

Defining the scale index as the ratio of the maximum length of the scale plate (the distance from its front edge, which is fixed in the body, to the free edge) to its greatest width allows you to get an idea of the sample's belonging to one or another ecological form.

In particular, for the sample of carp, this average value of the scale index was 1.1 ± 0.02, and for the sample of crucian carp, it was 1.06 ± 0.02. This allows us to state that the fish of the studied species in the conditions of the Horyn River belong to fast-growing forms.

Analysis of the conditions of the water environment of the Horyn River

The summarized results of the concentrations of hydrochemical parameters of the river and the ecological assessment of the quality of the water environment are presented in Table 5 (see p. 366–367).

Thus, the integral ecological index of the quality of the surface water of the river below the sewage discharge of the city of Dubrovitsa (site № 1) is characterized, according to the data of 2020, by the third category of the II class – the condition is "good", the degree of purity is "clean".

At the same time, the block of tropho-saprobiological indicators had 4.4 category III class – the condition is "satisfactory", the degree of purity is "contaminated". The block of specific indicators of toxic action had a value of category 3.6, which corresponded to the transitional state from II to III class – the state "good-satisfactory", the degree of purity "clean-contaminated". The block of indicators of the salt composition had 1 category of the I class.

On the border with Belarus, within the village Smorodsk (site № 2), the integral ecological index of the surface water quality of the Horyn river did not exceed the values of category 3.3, which is assessed by the II class of water quality – the condition is "good", the degree of purity is "clean".

Table 5. Hydrochemical indicators of the Horyn River and assessment of water quality according to the relevant categories

Year	Indicators	SO_4^{2-}, mg/dm³	Cl^-, mg/dm³	Ia	Suspended solids, mg/dm³	pH	NH_4^+, mg/dm³	NO_3^-, mg/dm³	NO_2^-, mg/dm³	PO_4^{3-}, mg/dm³	COD, mgO_2/dm^3	BOD_5, mgO_2/dm^3	Dissolved oxygen, mgO_2/dm^3	Ib	Fe^{2+}, mkg/dm³	Cu^{2+}, mkg/dm³	Zn^{2+}, mkg/dm³	Mn^{2+}, mkg/dm³	F_2, mkg/dm³	Ic	Ie
1		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Water intake #1 – river Goryn, within the Dubrovytsia city, 0.5 km lower of water discharge from treatment facilities of ME “Myskvodokanal”																					
2020	min	39.5 1	16.31 1	1.0	6.4 2	8.18 4	0.190 2	0.00 1	0.076 7	0.92 7	22.3 3	2.07 3	10.87 1	3.3	380.0 2	5.0 4	26.0 4	12.0 2	220.0 5	3.4	2.6
	max	53.3 2	20.56 1	1.5	11.6 3	8.37 4	0.230 3	6.39 7	0.090 7	1.35 7	44.8 6	4.48 5	10.86 1	4.8	380.0 2	5.0 4	26.0 4	12.0 2	970.0 6	3.6	3.3
	aver	46.4 1	18.44 1	1.0	9.0 2	8.28 4	0.210 3	3.20 7	0.083 7	1.14 7	33.55 5	3.28 4	10.87 1	4.4	380.0 2	5.0 4	26.0 4	12.0 2	600.0 6	3.6	3.0
Water intake #2 – river Goryn, within the Vysotsk village, on the border with Belorussia																					
2017	min	31.0 1	15.6 1	1.0	4.0 1	8.1 3	0.000 1	0.66 4	0.024 5	0.17 5	24.00 3	2.28 4	11.8 1	3.0	160.0 1	3.0 4	12.0 2	11.0 2	170.0 4	2.6	2.2
	max	43.2 1	25.8 2	1.5	15.4 3	8.48 5	1.630 6	3.11 7	0.069 6	0.83 6	54.20 6	5.94 5	6.1 4	5.3	280.0 2	9.0 4	27.0 4	23.0 2	310.0 5	3.4	3.4
	aver	37.23 1	19.88 1	1.0	7.19 2	8.22 4	0.441 4	1.68 6	0.041 5	0.45 5	34.93 5	3.25 4	9.53 1	4.0	220.0 2	6.0 4	18.0 3	17.0 2	320.0 5	3.2	2.7
2018	min	51.8 2	30.25 2	2.0	1.60 1	7.18 1	0.330 4	8.40 7	0.010 3	0.29 4	16.50 3	3.35 4	9.23 1	3.1	40.0 1	30.0 6	52.0 5	10.0 2	—	3.5	2.9
	max	92.4 3	43.25 3	3.0	13.2 3	7.69 2	1.200 6	23.87 7	0.062 6	0.66 6	36.50 5	5.61 5	7.09 3	4.8	250.0 2	32.0 6	68.0 5	14.0 2	—	3.8	3.8
	aver	72.07 2	34.98 3	2.5	8.53 2	7.43 1	0.810 5	17.62 7	0.042 5	0.48 5	28.70 4	4.19 5	8.24 1	3.9	140.0 1	31.0 6	60.0 5	12.0 2	—	3.5	3.3

End of Table 5

1		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
2019	min	53.3 2	4.254 1	1.5	15.8 3	7.65 2	0.33 4	0.04 5	0.010 3	0.14 3	29.3 4	1.57 2	9.96 1	3.0	140.0 1	8.0 4	10.0 2	10.0 2	200.0 4	2.6	2.4
	max	54.1 2	16.31 1	1.5	17.2 3	7.8 2	0.41 4	0.06 6	0.062 6	0.59 5	53.8 6	4.91 5	9.12 1	4.2	199.0 1	16.0 5	18.0 3	18.0 2	200.0 4	3.0	2.9
	aver	53.70 2	10.28 1	1.5	16.50 3	7.73 2	0.37 4	0.05 5	0.04 5	0.37 5	41.55 6	3.24 4	9.54 1	3.9	169.50 1	12.00 5	14.00 2	14.00 2	200.00 4	2.8	2.7
2020	min	27.5 1	12.1 1	1.0	7.0 2	7.98 3	0.2 2	4.0 7	0.06 6	0.24 4	20.9 3	1.63 2	12.9 1	3.3	110.0 1	16.0 5	13.0 2	11.0 2	240.0 5	3.0	2.4
	max	87.1 3	19.1 1	2.0	13.6 3	8.1 3	0.7 5	9.8 7	0.08 6	0.26 4	28.4 4	5.27 5	8.26 1	4.2	230.0 2	20.0 5	20.0 3	100.0 4	260.0 5	3.8	3.3
	aver	57.30 2	15.60 1	1.5	10.30 2	8.04 3	0.45 4	6.90 7	0.07 6	0.25 4	24.65 3	3.45 4	10.58 1	3.8	170.00 1	18.00 5	16.50 3	55.50 4	250.00 5	3.6	3.0
2021	min	48.1 1	12.10 1	1.0	2.0 1	7.8 2	0.079 1	3.0 7	0.03 5	0.21 4	17.0 3	1.53 2	14.42 1	2.9	110.0 1	7.0 4	9.0 1	13.0 2	210.0 5	2.6	2.2
	max	71.8 2	21.30 2	2.0	10.4 2	8.52 5	0.3 3	8.4 7	0.13 7	0.35 5	25.8 4	4.06 5	10.76 1	4.3	293.0 2	18.0 5	16.0 3	140.0 5	350.0 5	4.0	3.4
	aver	59.95 2	16.70 1	1.5	6.20 2	8.16 4	0.19 2	5.70 7	0.08 6	0.28 4	21.40 3	2.80 4	12.59 1	3.7	201.50 2	12.50 5	12.50 2	76.50 4	280.0 5	3.6	2.9

The categories of the tropho-saprobiological block determined the III class of water quality during the entire studied period. Water quality according to the block of specific toxic substances varied from class II to transitional class II–III. The block of indicators of the salt composition was mainly in the transitional I–II class – the condition is "excellent-good", the degree of purity is "very clean-clean". The exception was the salt block category in 2020 (2.5), which assigned the water quality to class I.

So, we can say that in recent years, the quality of the surface waters of the Horyn River is relatively favorable in terms of its ecological status, and therefore quite satisfactory for the life of representatives of the ichthyofauna.

Estimation of stability of fish development by fluctuating asymmetry of meristic traits

Developmental stability is one of the most general characteristics of organisms, which is supported on the basis of genetic co-adaptation under optimal development conditions: "… developmental stability is the ability of an organism to form a phenotype without ontogenetic violations and errors." An indicator of developmental stability can be fluctuating asymmetry (FA) – minor undirected deviations from bilateral symmetry in the structure of various morphological structures.

It is believed that the FA indicator is a measure of the stability of the development of a group of individuals, not an individual. An increase in FA at the group level indicates the destabilization of the development process in the population, the state of which ultimately depends on both the preservation of individual species and the normal functioning of the ecosystem as a whole.

The levels of fluctuating asymmetry of meristic features in the analyzed fish species were statistically reliable according to the Student's test (for $P \leq 0.05$) in the vast majority of cases, which allows us to talk about the response of the morphological homeostasis of the representatives of the ichthyofauna of the Horyn River to the ecological conditions of the habitat.

Statistical reliability at the level of $P \leq 0.01$ was characteristic of the asymmetry of meristic features of silver crucian carp in both reaches of the river, which, as the results of currently known research show, is explained by the resistance of this species to adverse factors in the aquatic environment.

The symmetry of the distribution of bilateral signs of representatives of the ichthyofauna of the Horyn River relative to zero (Fig. 8) shows that in both bodies for the analyzed fish species, the highest FA levels were characteristic of such signs as the number of gill petals in the first gill arch (sp. br), number of rays in pectoral (P) and ventral (V) fins.

In general, the frequency of asymmetric manifestation of symptoms (APS) for representatives of carp in the Horyn River had the following series of decline:

– site № 1: *sp. br > P > V > jj > f. br. > jjsk = Squ1 > Squ2 = Squpl*;
– site № 2: *sp. br > V > P > jjsk > jj > f. br. > Squ1 = Squ2 > Squpl.*

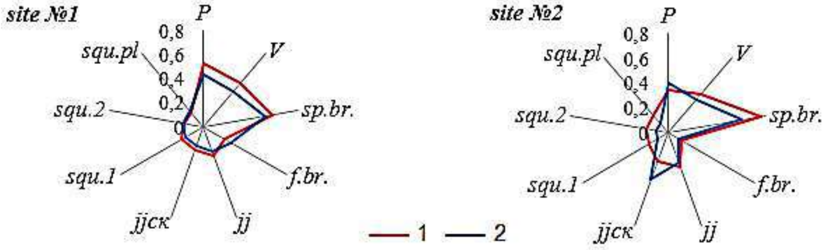

Figure 8. The frequency of asymmetric manifestation of paired meristic features of fish of the Horyn River:
1 – *Cyprinus carpio*; 2 – *Carassius gibelio*

In site № 1, the characteristics of the stability of the carp development according to the FAM (0.37 ± 0.07) corresponded to the III point and characterized the quality of the water environment as “the average level of deviations from the norm”. The stability of crucian carp development (0.30 ± 0.07) was assessed with II points. The average values of FAM and FAMT of the analyzed samples of fish in this stock corresponded to the II points, which assessed the quality of the water environment as “initial (minor) deviations from the norm”.

The higher average values of FAM in site № 2 were typical for carp (0.28 ± 0.05), although they corresponded to the I score of the quality of the water environment. The stability of crucian carp development (0.20 ± 0.04) was also at the level of the I score, which characterized the quality of the water environment as "conditionally normal". Therefore, the average values of FAM and FAMT of fish in this stock corresponded to the 1st point, which assessed the quality of the water environment as "conditionally normal".

Thus, the general morphological homeostasis of representatives of carp fish of the Horyn River can be considered relatively stable in both observation sites.

CONCLUSIONS

Evaluation of the morphophysiological characteristics of representatives of the ichthyofauna of the Horyn River within the Vysotsk village was conducted for representatives of carp (Cyprinidae): carp (*Cyprinus carpio*) and silver crucian carp (*Carassius gibelio*) in 2021.

The amount of variation in the size and weight characteristics of all analyzed fish species had the following decreasing order: fish body weight (m) > total length (ab) > Smith length (ac) > short length (ad) > greatest body height (gh) > head length (ao) > least body height (ez) > eye length (np) = eye height (rs).

Sufficiently high coefficients of fish fattening (for *C. carpio* 5.46 and 5.13, and for *C. gibelio* 6.11 and 5.73 according to Fulton and Clark, respectively) allow us to make assumptions about their sufficient supply of natural feed base and good physiological condition.

Fish samples for reverse growth calculations were represented by age categories from peers (1+) to four-year-olds (4+). In the analyzed retrospective, more accelerated growth rates of fish were noted in the second year of life (+83.28% and +96.27%, respectively, for carp and silver crucian carp). The scale index of both types of fish proves that the studied species can be classified as fast-growing forms in the conditions of the Horyn River.

The ecological quality of the surface waters of the Horyn River during the years during which the peculiarities of the ontogenesis of carp representatives were studied were characterized by a transitional state from “good” to “satisfactory”.

The stability of fish development, assessed by the levels of fluctuating asymmetry, corresponded to the II score within the catchment after the discharge of wastewater to the Horyn River (site № 1) and the I score in site № 2, where there is no increased anthropogenic load.

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THE TRANSITION ON ORGANIC TECHNOLOGIES IN AGRICULTURE AS A WAY OF ADAPTATION TO CLIMATE CHANGE

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INTRODUCTION

Global warming on the planet has unpredictable consequences, endangers the agricultural industry, including the cultivation of various agricultural crops. According to the decisions made at the UN level, it is planned to reduce greenhouse gas emissions by 45% by 2030. By 2050, this indicator should reach zero. However, the world has not yet reached a general agreement.

The climate continues to change relentlessly, and agricultural producers must adapt to these changes. Considering the negative impact of agricultural production on the environment, another task for agricultural producers is to reduce this impact.

The decline of nature, the current state of biodiversity is characterized by the fact that a significant number of species are under threat of extinction. Land degradation and its pollution have led to a 23% decrease in the productivity of the land surface. One of the biggest factors of soil pollution, which threatens the existence and development of rural areas and contributes to global warming, as well as deepening the food and food security crisis, is unsustainable agriculture.

According to the latest report of the Intergovernmental Panel on Climate Change (IPCC), up to 30% of global anthropogenic greenhouse gas emissions are caused by food systems. In addition, the use of agrochemicals in the cultivation of agricultural crops and the production of food causes emissions of most nitrogen compounds into the atmosphere.

Farmers suffer the most negative consequences from an unstable economy, especially in terms of food security and climate change. But, unfortunately, according to the analysis of experts, of the 700 billion dollars allocated by leading countries to support farmers per year, only 1% is used to solve environmental problems.

It is obvious that sustainable food also requires the protection of environmental resources used in the food chain.

In recent decades, the issue of climate change has become the next task of environmental protection for the world society. Ukraine does not stand aside. Extreme weather events in areas where they were previously rare, intense heats and droughts are causing climate zones to change. And all this affects the state of the natural environment, including the production of agricultural crops, the state of forests and water bodies, and other sectors of the economy (Climate change and agriculture in Ukraine…, 2019).

The climate changes that have occurred in the last 30 years are anthropogenic in nature, as humanity has interfered with nature throughout its development and continues to do so. And this is the main source of greenhouse gas emissions.

The main stressful weather factors in the cultivation of agricultural crops are a lack of moisture and a sharp change in temperature. In order to ensure stable and high-quality harvests, farmers need to compensate the deficiency of moisture with irrigation, allow control of evaporation, apply measures to prevent stress due to high and low temperatures.

In Ukraine, global warming, which is a consequence of climate change, has an obvious impact on agriculture. But agriculture, which often suffers from climate change, is at the same time a source of greenhouse gas emissions, and therefore a cause of this change. For example, agriculture (animal husbandry, plant breeding) is a source of emissions of carbon dioxide, methane and nitrogen oxide. According to emissions reports that governments provide to the Secretariat of the United Nations Framework Convention on Climate Change, agriculture accounts for approximately 15% of global greenhouse gas emissions. On the other hand, greenhouse gases change the climate and thus affect agricultural production. Besides, the share of agriculture in world GDP is about 4%, and this is an indicator that the volume of emissions per unit of produced products (carbon intensity of agricultural production) is high.

Transitioning to agriculture based on sustainable production models, including organic production principles, can be a solution to implementing sustainable food systems and ensuring resilience to climate change.

Agriculture based on organic technologies is the most affordable farming system to support smallholders, who practice subsistence farming and procure local resources at little cost.

The formation of agrarian policy, including in the field of food, should take into account of all modern challenges: the development of the energy industry, the state of the environment, climate change, food security, the availability and volume of financial resources. This will contribute to sustainable agriculture, including support for organic farmers.

At the end of the 90s of the last century, domestic agricultural producers began to realize the need to transition and implement organic technologies. Over the last decade, while developing the domestic organic market, Ukraine has become one of the leaders in the international market of organic products. This is observed both by the size of the agricultural lands used for growing organic crops and by the number of market operators. At the same time, the range of domestic organic products and the geography of their sale are also expanding.

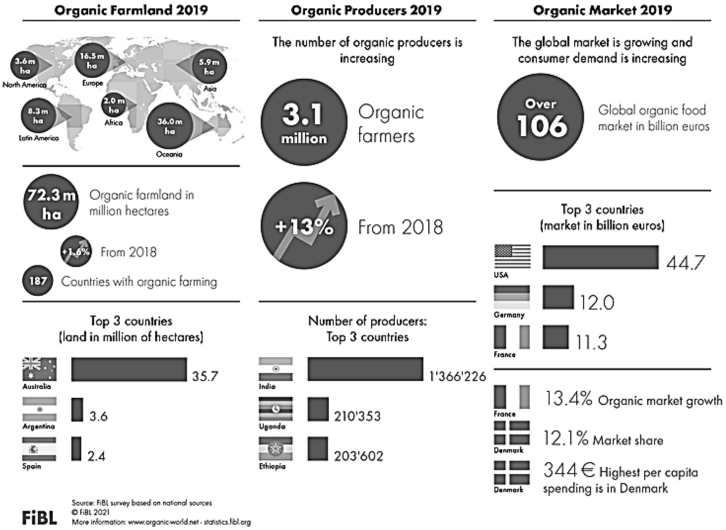
The development of the organic domestic market is taking place against the background of the dynamic development of the organic products market in the global world. According to the International Federation of Organic Agriculture Movements (IFOAM), the last two decades have seen a significant increase in the development of organic agriculture and organic production in the world. This is associated with the increase in environmental awareness of the population and the increase in demand for safe food products. In turn, agricultural producers gained confidence that consumers are ready to pay a higher price for products grown using organic technologies.

Analyzing the number of producers of organic products in the world from the beginning of the 2000s to our time, it can be noted that it has increased more than 10 times and in 2021 was almost 3.7 million subjects. More than 2/3 of all manufacturers are concentrated in the countries of Asia, Africa and Latin America. As for the countries with the largest number of them, these are India, Ethiopia, and Tanzania. Almost 75 million hectares of land are used for organic production in the world (annual growth over the last 3–4 years is from 2 to 4%). The largest areas are concentrated in Oceania and South America – about 40.0 million hectares (Fig. 1, *a*, *b*, *c*) (The World of Organic Agriculture Statistics…, 2021, 2022, 2023).

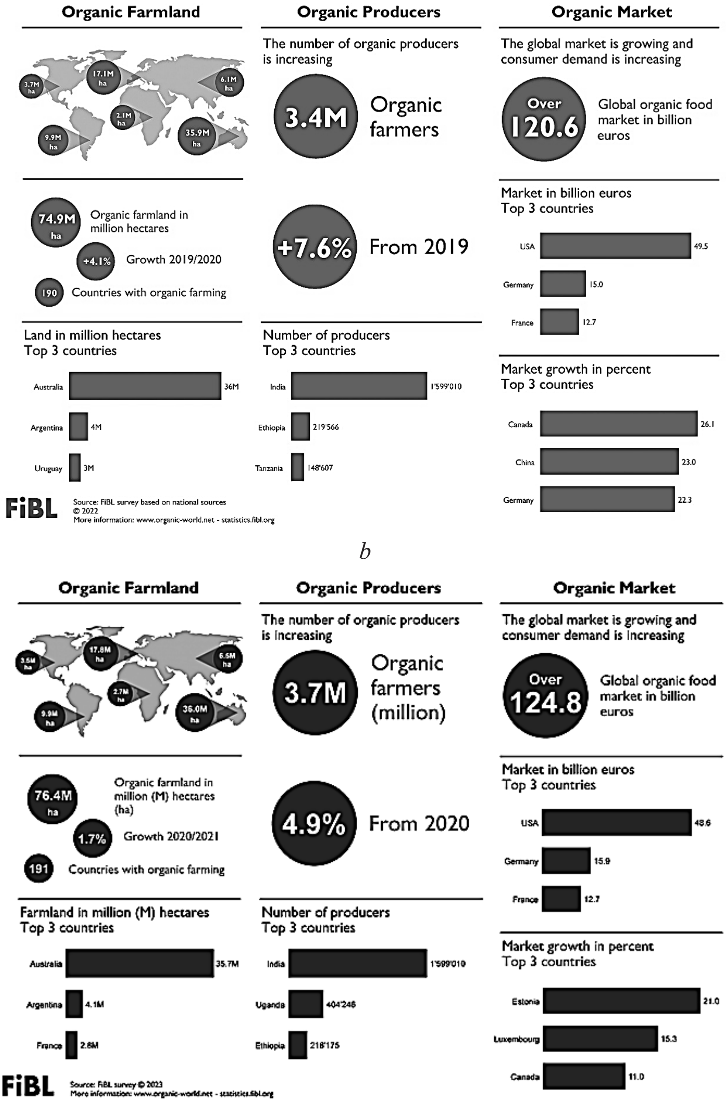
Europe ranks second in terms of the area of organic agricultural land (more than 17 million hectares). France is among the TOP-3 countries with the largest areas of organic land (Fig. 2, see p. 378). Moreover, over the past three years, the area of organic land has increased on all continents.

MATERIALS AND METHODS

The purpose of the work was to consider ways of greening agriculture through the transition to organic technologies



a



b

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Figure 1. Organic Agriculture Worldwide: *a* – 2019; *b* – 2020; *c* – 2021

Source: FiBL, www.organic-world.net – statistics.fibl.org in the conditions of adaptation to climate change, as one of the models of sustainable development of the industry. To analyze the trends and dynamics of the development of the organic market in the world and in Ukraine. The research used reports and statistical data of the Food and Agricultural Organization of the United Nations, researches of the World Bank. The analysis of the state of the organic market and the dynamics of its development was carried out using the reports of the Federation of the Organic Movement of Ukraine and certification bodies.

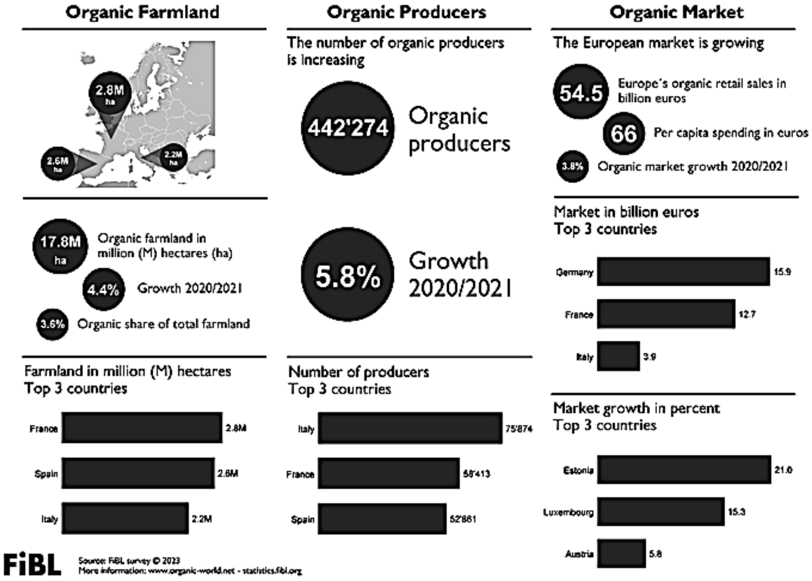

Figure 2. Organic Agriculture in Europe (2021)

Source: FiBL, www.organic-world.net – statistics.fibl.org

RESULTS AND DISCUSSION

According to the observations of specialists of the State Hydrometeorological Center, the Ukrainian climate is more sensitive, and warming is happening faster than in general in the world. Yes, the years 2019–2020 were the warmest in global measurement. The average annual air temperature exceeded the norm by three degrees. Moreover, over the last 20–25 years, the highest temperatures ever observed during the entire period of meteorological observations were observed in most of the territory. Temperatures above +(30–35) degrees were increasingly recorded in areas where they had never been observed before, which caused premature ripening of all agricultural crops. But, at high temperatures, the growth and development of almost all agricultural crops stops, which leads to a decrease in yield.

According to the same observations, the thermal resources of the territories have increased significantly. It became possible to grow almost all crops with increased requirements for heat supply. But plants for which extremely high temperatures occur gradually shorten the growing season and, accordingly, yield. Thus, it becomes impractical to grow certain agricultural crops in the respective regions (Kovalchuk, 2022).

Another important indicator for agriculture is annual precipitation. In Ukraine, the norm is 578 ml. But sustainable agriculture requires at least 700 ml. The average figure for the last 5 years is 553 ml, and for the last year – 557 ml. This situation is the basis for future droughts. According to experts, the rate of annual precipitation is often provided due to short-term intense downpours, when a month's rate of precipitation or more can fall in one day, which washes away everything. Moreover, the number of such ineffective rains is increasing. The effectiveness of these precipitations decreases due to an increase in temperature and an increase in evaporation. Today 90% of the steppe zone of Ukraine needs irrigation.

At the beginning of 2022, the World Bank presented the report "Ukraine: Resilience to Climate Change in Agriculture and Forestry", which presented the results of detailed research on the impact of climate change in Ukraine on the two most vulnerable industries. It confirmed the forecasts of domestic experts (Ukraine – Building Climate Resilience in Agriculture and Forestry…, 2022). This analysis is especially important for agriculture, which is a key aspect of the national economy and job creation. According to the analysis, starting from the 80s of the last century, Ukraine is experiencing accelerated warming, which is why the temperature will continue to rise. Without measures to mitigate the impact of climate change, temperatures are projected to rise by more than 4 °C by the end of the century. The regions located in the east and northeast of Ukraine (Kharkiv, Luhansk, Sumy) are most affected, while the regions in the west (Ivano-Frankivsk, Lviv, Volyn) are the least affected. It is predicted that the number of summer days will increase to 135 days a year for the southern steppe by the end of the century. An increase in air temperature may lead to heat and increased aridity in the south and east of Ukraine. This will reduce the number of frosty nights in these regions by 22 days. Such changes will undoubtedly affect the health of the population and the city infrastructure.

According to the Report (Ukraine – Building Climate Resilience in Agriculture and Forestry…, 2022), annual precipitation is also projected to increase, but these changes will be highly unpredictable. So, towards the end of the century, the summer months will become drier and the amount of precipitation will decrease. In winter, on the contrary, an increase in the amount of precipitation per month is expected in almost the entire territory of the country. Moreover, more precipitation is expected in the northwest (Rivnenska, Volynska), with a decrease in the summer months in the south and west. The least increase will have southern and central regions with some reduction in the warmer months.

Extreme weather and climate events will be observed throughout the territory, including heat, thunderstorms, floods and droughts, etc.

Climate changes will have a tangible impact on the agriculture of Ukraine: a significant decline and a possible decrease in the yield of agricultural resources; changes in sowing and harvesting dates for various grain crops due to temperature fluctuations and mineral precipitation. According to agricultural scientists, for example, the yield of barley, corn and sunflower could decrease by 10–30% in 2030–2050 compared to 2010, while the yield of winter wheat could increase by 20–40% in the north and northern forecast western Ukraine by 2050 compared to 2010.

Of course, such projections can be used to some advantage to increase yields of some grain and technical crops depending on changes in temperature and precipitation patterns by mid-century. But if we look at the effects of global warming on the industry as a whole, without measures to adapt to climate change, the industry faces significant losses that will lead to a significant loss of household income, increased poverty and inequality in various regions.

Climate change will have different impacts on different regions, based on its impact on agricultural production and the impact on population poverty rates.

In the period until 2030, among the regions where agriculture will be most affected by climate change, there are five ones – Cherkasy, Kherson, Kirovohrad, Poltava, and Vinnytsia. In the Kyiv and Zhytomyr countries, with a decrease in the amount of precipitation in the spring-summer period, some losses in agriculture may reach 40–60% by 2050. Although the agricultural sector makes a small contribution to the GDP of these areas, the projected changes in the value of agricultural production have significant research on measures to overcome economic inequality. Lviv and Zhytomyr regions have the largest losses to the reduction of projected precipitation in spring and summer in full measure, together with loss of income from agricultural production until 2030.

Under conditions of timely adaptation, Ukraine can reduce economic risks for agriculture and forestry and expand opportunities in these sectors.

Ukraine should take measures to reduce the risks and opportunities of use that climate change causes for agriculture.

Based on the analysis presented in the Report (Ukraine – Building Climate Resilience in Agriculture and Forestry…, 2022), as well as from international experience, several areas of adaptation of the industry to climate change were recommended. One of them, there was the promotion and support of the transition to climate-balanced (climate-smart) agriculture, the improvement of the system of subsidizing one and insurance involving the support of farmers in their implementation of climate-smart technologies and special insurance to cover the remaining risks from climate change, which is not violated by adaptation actions.

Among the climate-smart technologies, the implementation of organic technologies in agriculture can be considered, and experts prefer them.

According to the Research Institute of Organic Agriculture FiBL (Switzerland) and IFOAM, there is a trend towards a rapid increase in areas under organic production in the world. In the annual statistical guide “The World of Organic Agriculture”, published on February 15, 2022, it is noted that the area of organic agricultural land in the world increased by 2.9 million hectares in just one year, 2020, as evidenced by data from 190 countries (data at the end of 2020) (The area of agricultural land under organic farming..., 2022).

A rapid increase in the area of land used for organic production and the number of producers of organic products is also observed in the countries of the European Union. In 2020, the area of agricultural land in Europe used for organic production was 17.1 million hectares, increasing annually from 0.6 to 0.9 million hectares, or by 4–5%. Similar trends were observed with regard to the increase in the volume of the organic market. So, in 2019 alone, the market grew by 8% and amounted to €45 billion. The growth rate slowed down a bit compared to 2018, but was much faster than in the first years of the last decade (The European organic market grew..., 2022).

To support the long-term sustainability of both nature and agriculture, the European Union has adopted an EU Biodiversity Strategy to 2030, which will work in conjunction with the Farm to Fork strategy and the new Common Agricultural Policy, including by promoting eco-schemes and schemes payments The implementation of strategies is aimed at stimulating the development of sustainable and organic agriculture, as well as reducing the use of harmful pesticides by 50% in order to reduce the negative impact on natural ecosystems and preserve pollinators (Gvozdyova, 2021).

In Ukraine, in recent years, there has also been a steady positive growth in the area of agricultural land on which certified organic production is carried out, both the number of organic market operators and the level of consumption of organic products are increasing. Official statistical reviews of IFOAM confirm that if in 2002 31 farms were registered in Ukraine, which received the status of "organic", then in 2021 there were already 528 organic operators, and the total area of agricultural land on which organic production is carried out amounted to 422,299 hectares. Although in recent years there has been a certain decline in the number of operators and areas under organic production (Fig. 3, Table 1).

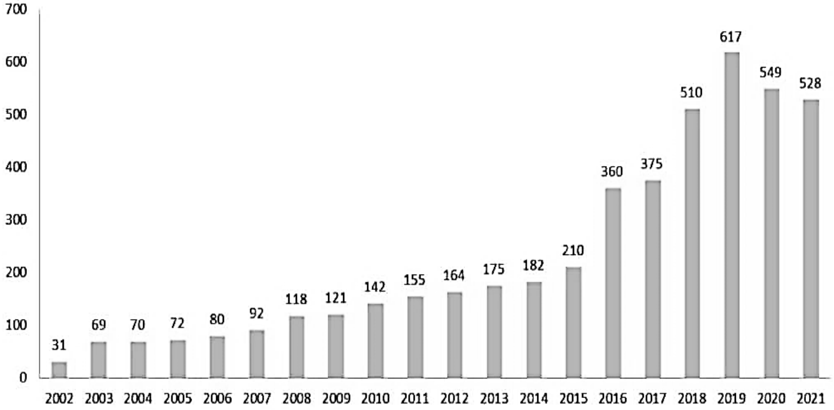

Figure 3. Number of organic operators in Ukraine

Source: according to IFOAM, the Federation of Organic Movement of Ukraine and the Ministry of Economy of Ukraine

Table 1. Total area of organic agricultural land (including the transition period) in Ukraine, 2002–2021

Year	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Area, thousand ha	164.45	239.54	240.00	241.98	242.03	249.87	269.98	270.19	270.23	270.32
Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Area, thousand ha	272.85	393.40	400.76	410.55	411.20	420.00	429.10	467.98	462.23	422.30

Source: according to IFOAM, the Federation of Organic Movement of Ukraine and the Ministry of Economy of Ukraine

Ukraine still lags behind the EU countries in a number of indicators (the percentage of organic land from the total area of agricultural land), but it has a fairly good growth rate. Before the pandemic, Ukraine was among the TOP-10 European countries in terms of the rate of increase in organic land over the past 10 years.

The majority of Ukrainian organic farms are located in Kyiv, Odesa, Kherson, Poltava, Vinnytsia, Zakarpattia, Lviv, and Zhytomyr regions. Ukrainian certified organic farms vary in size from a few hectares, as in most European countries, to several thousand hectares of agricultural land. Given the growing number of small organic farms, their specialization is primarily focused on the cultivation of fruit and vegetable and berry products. However, the export orientation of producers, especially legumes and berries, remains a fact.

According to experts, in recent years, the positive dynamics of the growth of the area of agricultural land on which certified organic production is carried out is also explained by the filling of the domestic market with domestic organic products and due to the establishment of own processing of organic raw materials. Domestic organic cereals, flour, dairy and meat products, eggs, juices, honey, oil, and teas appeared on the shelves of supermarkets and specialized retail chains. Data on the annual growth of the domestic consumer market of organic products is presented in Table 2.

According to the National Economic Strategy of Ukraine until 2030 approved in the spring of 2021, one of the goals is to increase the area of agricultural land under organic production. This indicator should

Table 2. Volumes of the consumer market of organic products in Ukraine, 2004–2021

Year			**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
million euros			0.1	0.2	0.4	0.5	0.6	1.2	2.4	5.1
Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
million euros	7.9	12.2	14.5	17.5	21.2	29.4	33.0	36.0	38.0	39.0

Source: according to IFOAM, the Federation of Organic Movement of Ukraine and the Ministry of Economy of Ukraine reach about 1.3 million hectares of land used for organic production, which will make up 3% of the total area of agricultural land. Another strategic goal is to increase the export of organic products to 1 billion US dollars by 2030.

Analyzing the opportunities and prospects of Ukraine, it should be noted that the European Union also has plans to increase the share of organic land. Thus, according to the "Farm to Fork" strategy, which is part of the Green Deal, the share of organic land in EU countries should reach 25% by 2030 (EU Biodiversity Strategy to 2030…, 2020). Among the main measures proposed to achieve this goal of the European Commission is to stimulate consumption; stimulation of production and development of sustainability of the sector and its contribution to environmental protection.

Since the EU countries are today considered as the main sales market for domestic organic products, the plans of the European Union are important for Ukraine. Domestic consumption of organic products in Ukraine is niche, that's Ukrainian producers consider this sector as an opportunity to increase their export potential (Fig. 4, see p. 386). The share of European countries in the export of Ukrainian organic products is 73%. The USA and Canada import about 24% of organic products from Ukraine. Currently, Ukraine ranks 4th in the world among 127 suppliers of organic products to the EU, second only to Ecuador, the Dominican Republic and China. At the same time, Ukrainian organic producers export more than 60 types of products: grain and oil crops, soybeans, sunflower oil, peas, fruits and berries, vegetables, mushrooms, nuts, greens and vegetable preserves, juices, flour, honey.

Today, the TOP-10 countries that are the most desirable for Ukrainian exporters include both traditional and new countries that are promising for trade. These included: Brazil, United Arab Emirates, Ethiopia, India, China, Kazakhstan, Chile, Qatar, Uzbekistan and Canada. Among other priority regions for exporters, the countries of the Middle East, the Asia-Pacific region, the countries of Africa, and the region of North and South America are considered.

Climate change and extreme weather conditions also carry financial losses. The International Finance Corporation (IFC) has estimated that over the past 20 years, natural disasters have led to the loss of more than 2 billion dollars in the agricultural sector. But, in addition to climatic risk factors, there are also such as: an increase in the prices of fertilizers, PPE, fuel, and the machinery itself. But, according to experts in climate-oriented agriculture there are ways to solve these problems using known technologies. This will allow sequestration (keeping in the soil) of greenhouse gases from the environment. Thus, agricultural producers can contribute to the preservation of the climate and reduction of negative consequences (Shlapak, 2019).

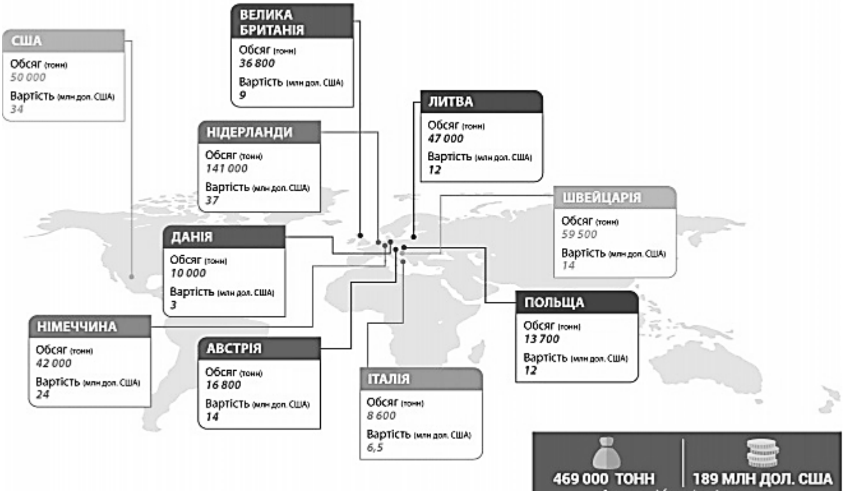

Figure 4. TOP-10 exporting countries
of Ukrainian organic products in the world, 2020

As already mentioned above, agriculture has been recognized by the Intergovernmental Panel on Climate Change (IPCC) as one of the most vulnerable sectors of the economy to climate change. Therefore, the development and support of sustainable agriculture in Ukraine, an efficient processing industry, and increasing international competitiveness can be one of the measures to adapt to climate change and to minimize losses in the industry. According to the IPCC report, the effects of climate change on crop production and food production are evident due to the negative impact of extreme daytime temperatures and increased concentrations of CO_2, which promotes the spread of weeds. Similarly, for Ukraine, the consequences and risks of climate change are diverse and will affect the agricultural sector. This explains the need to introduce specific agro technical measures in order to increase the effectiveness of climate change adaptation measures. The main task of adaptation measures is to reduce vulnerability to the effects of climate change. Often they contribute to the reduction of greenhouse gas emissions, thus creating benefits to prevent climate change.

The key consequences of climate change and the vulnerability caused by them were taken into account when developing the Strategy for Adaptation to Climate Change of Agriculture, Forestry and Fisheries of Ukraine until 2030. The same factors should be taken into account during the development of specific program and technological adaptation measures to minimize the negative impact of climate change on food security and competitiveness of the agricultural sector of Ukraine (The Strategy for environmental security…, 2021).

Based on the assessment of the technological needs of the agricultural sector of Ukraine by international experts and discussions with interested parties, priority technologies were determined both to prevent climate change and to adapt to its consequences in the agriculture of Ukraine, including those presented in Table 3 (Ukraine – Building Climate Resilience in Agriculture and Forestry…, 2022).

Table 3. Technologies for adaptation to climate change and prevention of its consequences in the agricultural sector of Ukraine

Technologies for adaptation to climate change	Technologies to prevent climate change	Potential relationship between politicians
The complex fight against pests and diseases	Organic agriculture (carbon absorption, avoidance of N_2O emissions from the use of mineral fertilizers, reduction of fuel consumption)	Policies to support organic farming, including the use of biological pest and disease control in organic agriculture

One of the important issues for the development of the organic market in Ukraine is the need to regulate the legal framework, which will ensure the activities of producers in accordance with domestic organic standards with appropriate control by both certification bodies and the state. With the aim of improving the principles of legal regulation of organic production, circulation and labelling of organic products and adapting the requirements of organic legislation to the legal norms of the European Union, with the support of the public sector and experts of the organic market, executive authorities, a new Law of Ukraine “On the basic principles and requirements for organic production, circulation and labeling of organic products” was adopted (No. 2496-VIII, entered into force on August 2, 2018, entered into force on August 2, 2019). First of all, the Law fully takes into account EU directives and regulations, which allows adapting Ukrainian legislation to European legislation; requirements for the production, labelling and circulation of organic products have been improved; the provision regarding the assessment of the suitability of land for the production of organic products, which was contrary to international practice, was removed; the principles of production certification have been fundamentally changed; requirements for certification bodies have been significantly improved; responsibility for violations of legislation in the field of production, circulation and labelling of organic products is specified, both for producers and for certification bodies.

An important stage in the development of sustainable agriculture in Ukraine was the adoption on November 5, 2020 of the Law of Ukraine “On Amendments to the Law of Ukraine ‘On State Support of Agriculture of Ukraine’ and other laws of Ukraine regarding the functioning of the State Agrarian Register and improvement of state support for producers of agricultural products.” The adopted Law provides for: reimbursement of up to 30 percent of the cost of certification of organic production and reimbursement of up to 30 percent of the cost of purchasing approved plant protection products and fertilizers, seeds, planting material and feed.

Among the tasks defined by the Strategy for Environmental Security and Adaptation to Climate Change for the period until 2030

(The area of agricultural land under organic farming..., 2022) and aimed at achieving the set goals are ensuring the development of organic agriculture, the use of economical land cultivation practices with the preservation and increase of soil organic matter.

The development of the organic sector is particularly important and promising for domestic agricultural producers, consumers and the state as a whole, especially in the context of food security, adaptation to climate change and environmental protection.

CONCLUSIONS

Considering that the technologies traditionally used in agriculture are, to a large extent, the reason for the decline of biodiversity, both global and regional strategies for the development of the agricultural sector should be directed to cooperation with farmers to support and stimulate their transition to sustainable technologies. Increasing the resilience of the agricultural sector to climate change and reducing environmental risks and socio-economic consequences will be carried out through improving the condition and diversity of agroecosystems. In addition, such a transition to sustainable technologies will contribute to the creation of new jobs in the field of organic farming, ecological tourism, etc.

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METHODOLOGY OF DEVELOPMENT OF PREVENTIVE NORMATIVE SUPPORT FOR ECONOMY ECOLOGIZATION

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INTRODUCTION

The key methodological vectors for the development of national economies worldwide include strategies such as survival through natural resource utilization, mitigating environmental, economic, and social factors, resource management, sustainable (systemic) development, ecologization, green economy, and others. According to analysts' estimates, to overcome negative environmental trends and gradually transition to a systemic development model, it is necessary to allocate 2–3% of GDP for the protection and restoration of the natural environment (the average norm for countries with a high GDP volume). For Ukraine, whose specific territories are often classified as zones of ecological distress with a significant ecological footprint, this allocation should be significantly higher. To ecologize the country's economy and implement its European integration direction, it is necessary to: ensure appropriate macroeconomic conditions, activate the market environment for eco-business, establish mechanisms for protecting the natural resource potential at the national level, enforce environmental legislation at all levels, significantly increase fines for pollution of the natural environment, and more.

The European Union has announced plans to become climate-neutral by 2050. In December 2019, the European Commission presented its vision for the development of the European continent, known as the "European Green Deal." The European Green Deal is a package of systemic policy decisions aimed at achieving climate neutrality and developing a just society on the European continent by 2050. While the European Green Deal is not a law, it represents the first step towards legally establishing effective resource consumption, greening investments, reducing greenhouse gas emissions, and achieving sustainable development and preservation of the natural environment based on preventive principles.

However, significant socio-ecological-economic development results for the country can be achieved with minimal costs for stabilization and conservation of the natural environment by implementing a methodology for the development of preventive legislative and normative support for ecologizing the economy and harmonizing it with the EU.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Methodological and theoretical-practical foundations for the conservation and rational use of natural resource potential have been addressed in the works of scholars from Sumy, Kyiv, Odesa, Lviv, Rivne, and other schools of natural resource economics. Some developments regarding the adaptation of legislative and normative documents, European directives, standards, and technical regulations are reflected in the publications of M. D. Balzhi, L. Melnyk, V. Pavlov, K. Papenov, L. Kupinets, P. Skrypchyk, I. Khovavko, O. Furdychko, and other researchers. Economic problems of European integration and the adaptation of Ukrainian legislation to the EU are investigated in the works of O. Akmentin, I. Andrushchenko, O. Bychenko, M. Basaraba, L. Galperina, M. Grebenyuk, N. Honcharenko, H. Druzenko, V. Didyk, O. Zerkal, V. Muravyova, I. Kravchuk, I. Kirovska, M. Kalina, O. Naumenko, O. Shnirkov, O. Chugayenko, O. Shompola, and other scientists (Stechenko et al., 2001; Varnalii, 2007; Hrebenuk et al., 2010; Martin-Breen et al., 2011; Economic aspects of natural resource management…, 2015; Skrypchuk et al., 2020; Inclusive rural development in Ukraine…, 2020; National Economic Strategy for the period up to 2030…, 2021).

The principles of preventiveness in researching the development potential of territories are dedicated to the works of well-known Ukrainian and foreign scientists such as H. Atamanchuk, V. Afanasiev, O. Voronov, D. Gvishiani, P. Drucker, V. Duncan,

G. Kunts, M. Mesarovic, P. Nadiolishniy, N. Nyzhnyk, O. Mashkov, V. Zinovchuk, V. Tolkovanov, S. Markovsky, M. Dolishniy, M. Zhuk, A. Granberg, and others (Shlemko, 1997; Dolishnii, 1999; The Global Green Finance Index 3…, 2019; The Future of Agricultural Cooperatives…, 2022; Agenda for the period up to 2030…, 2022; Ukraine 2022…, 2022).

The aim of the article is to develop methodological foundations for the development of preventive normative support for the ecologization of the economy.

DISCUSSION

The information and normative support for decision-making and timely exchange of information regarding potential undesirable events (such as risks in various economic sectors, natural resource conservation, quality of vital resources, etc.) are important components of prevention in addressing socio-ecological-economic challenges. The methodological foundations of prevention are based on the principles of a systemic approach applied in all areas of human activity. Based on the nature of normative and legislative activities, prevention is and will always be a methodological objective and basis for all forms of standardization, metrology, and certification. These fundamental principles are recognized in the standards principles of ISO (International Organization for Standardization), IEC (International Electrotechnical Commission), and other specialized non-governmental organizations involved in the development of normative documents, directives, codes, rules, and so on.

In particular, the United Nations and the United Nations Economic Commission for Europe rely on developed recommendations regarding the policy in the field of standardization. Starting from the 1970s, the importance of international standardization and its methodological (preventive) approaches have been recognized by intergovernmental bodies and conferences, such as the Conference on Security and Cooperation in Europe, the Agreement on Technical Barriers to Trade of the World Trade Organization (which incorporates relevant articles on harmonized and preventive instruments of control and interaction in different countries), the Regional Agency (in Europe) for policy coordination, forums for intergovernmental discussion of issues related to standardization, conformity assessment, and related activities, such as metrology, and more. As a result, the following recommendations regarding the policy in the field of standardization are used worldwide: international cooperation in the field of technical regulation and standardization; coordination of activities and harmonization of standards and technical regulations on an intergovernmental scale; development of international agreements on simplification of conformity assessment and recognition of its results; methodological research and personnel training; development of innovative metrological support, and more.

Therefore, the adaptation and implementation of normative documents from economically developed countries and the EU in Ukraine should become a prerequisite for harmonizing socio-ecological-economic relations and the dominant factor in national environmental policy. This, in turn, initiates further activation towards the development of a national concept of systemic development and the implementation of effective models for its implementation. Simultaneously, the process of developing standards, technical regulations, and laws should also undergo transformation. Currently, this process is aligned with global standards but requires the involvement of more experts, taking into account the peculiarities of building a civil society, the responsibility of officials for the process of openness and norm-setting. The main attention should be focused on the legislative regime and the specification of the foundations of regionalization regarding the establishment of effective regulatory and incentive mechanisms for nature conservation.

One of the effective tools for the preventive development of normative support is adaptation: aligning legislation with EU norms and rules, removing customs barriers, reforming the judicial system, and establishing a new institutional system that includes new decision-making procedures for Ukraine. Real progress is needed for Ukraine’s integration into the EU, which will improve the quality of life for its citizens. Currently, the EU is a strategic partner for Ukraine, and the share of the EU in the overall structure of foreign trade turnover is constantly increasing, reaching 31.2% in 2013. The foreign trade turnover between Ukraine and EU countries amounted to $8.1 billion in 2013, with a positive balance of $1.4 billion (Shvaika, 2013).

It should be noted that exporters interested in European markets will be the first to adapt to EU standards since the success of their activities is not possible without meeting the requirements of practically all environmental directives and a large number of standards. The state interest lies in the implementation of the European integration vector in institutional reforms and the infrastructure, which will yield much greater benefits than without EU membership. The state's function is to create a favorable climate, reduce taxes, and fully support them compared to the existing ones at present.

The methodology of preventive development of regulatory support should serve the environmental modernization and societal interests in the search for innovative paths of eco-oriented development. This involves advancing science and applied research to update production methods based on the most accessible and clean technologies, accompanied by the penetration of cutting-edge developments into the field of communications (information society) and other spheres of life.

European experience is being adopted in Ukraine through various projects and programs, such as the green and white paper formats, along with discussions of these documents with stakeholders. Such papers serve as tools for shaping policies and making governmental decisions in the EU. The purpose of the green paper is to reflect the complete policy-making cycle, from problem formulation to evaluating policy implementation results. Through the white paper, the government deepens its dialogue with the public, initiated during the preparation of the green paper, and formulates its own position and vision for addressing issues in state environmental policy. The white paper contains specific proposals for overcoming, for example, environmental problems and developing new high-tech standards to address various issues. When a solution that is acceptable to both political leadership and key stakeholders in society is found, the proposals outlined in the white paper are submitted to the Cabinet of Ministers or the Verkhovna Rada in the form of a legislative act draft.

Therefore, the mentioned aspects of adaptation and greening are inseparable, which, on the one hand, brings new opportunities for the state and businesses, but on the other hand, can result in significant losses and problems. In such a situation, consumers prefer the most competitive and environmentally responsible products, which encompass technologies, production processes, packaging recycling, social responsibility, and other aspects of the "green" economy. Thus, the development of science, technology, ecological culture, and democratic values encourages inclusive processes that form the basis for the most progressive long-term solutions. Later, these ideas are standardized into innovative solutions, designs, technologies, projects, etc., contributing to the formation of transformed eco-economic relations and more.

This is where the preventive nature of standardized innovations in the economy, ecology, and social sphere manifests itself. Hence, the methodology of preventive development of regulatory support should facilitate environmental modernization and direct societal interests towards innovative paths of eco-oriented development. Such transformative processes result in the reorientation of priorities in state socio-economic policies, including stimulating the development of the service sector, improving social protection policies and income redistribution, for instance, through the implementation of ISO 26000 standards on business social responsibility in Ukraine.

Considerable attention is currently being given worldwide to the development of preventive strategies for addressing environmental issues. In this context, two complementary preventive industrial strategies are highlighted: Cleaner Production and Eco-efficiency Strategy. However, it can be observed that the reorientation of production potential towards new technologies and innovative environmental management methods is progressing too slowly. One approach that has proven effective in many countries, both developed and developing, is the implementation of environmentally friendly production in the industrial, agricultural, and service sectors.

The transition to environmentally safe and cleaner production will create the conditions for aligning national policies in the areas of restructuring, modernization, and development of national economic sectors, as well as in the provision of services, with the policy of environmental protection, rational use of natural resources, and improvement of quality of life for the population, aiming for gradual transition to sustainable development.

An example of a preventive approach is the online consultations of the Food and Agriculture Organization (FAO) regarding the improvement of the Rome Food Agreement. For instance, point 21 of the Further Actions states: “Recognizing that changing the configuration of the global food system to enhance the quality of food for people, especially women and children, requires a framework program for collective commitments in the following areas: the linkages of food systems (production, storage, and distribution systems) to health needs” (National Economic Strategy for the period up to 2030…, 2021). Therefore, standards regarding quality food production will be included in framework documents, agreements, and directives, which will reduce mortality and improve health, among other things.

Another example of a preventive approach is the implementation of provisions related to the renewability of biofuels and biomass, which is an important aspect of preparing the Action Plan for Sustainable Energy Development (Regulation on the sustainability…, 2009; Regulation on the sustainability of biofuels…, 2009; Directive 2009/28/EC…, 2009; Kandul, 2010).

In general, biomass and biofuels represent a form of renewable energy whose utilization does not have an impact on the concentration of CO_2 in the atmosphere. However, this is true only if they are produced in a sustainable manner. The combustion of carbon with bioorganic origin, such as in wood, bio-waste, or transportation biofuels, results in the formation of CO_2. However, these emissions are not accounted for in CO_2 emission inventories if it can be assumed that the carbon released during combustion is equivalent to the carbon absorbed by biomass during growth over the course of a year. In such cases, the standard emission coefficient for biomass and biofuels is considered to be zero. This assumption is often important for agricultural crops used for biodiesel and bioethanol production, as well as for wood if forest management is based on a renewable approach. This means that, on average, forest growth equals or exceeds logging.

However, biomass and biofuels will have a neutral CO_2 balance, and their utilization will not be considered rational if there are significant emissions of other greenhouse gases, such as N_2O from fertilizer use or CO_2 from land-use change, or if the production process has a negative impact on biodiversity. Therefore, local communities are recommended to assess this in the environmental auditing process.

Therefore, the implementation of the concept of resource-efficient and cleaner production as the first practical legal element of the systemic development strategy is justified. This concept entails ways to address the problem and justify the optimal option for the preventive development of economic ecologization. Taking into account the options for implementing systemic development in Ukraine (Sustainable Development Strategy..., 2013), a methodology for preventive development of legislative and regulatory support through the modernization of organizational-economic, institutional, incentive, and socially responsible mechanisms, as well as the corresponding socio-ecological-economic instruments of implementation, has been proposed.

An integral part of such a methodological approach is the formation of a system of resource-efficient and cleaner production by shifting the main focus from monitoring the situation and overcoming consequences to the modernization of technologies, processes, and management systems in all sectors of the economy. These approaches need to be implemented through the introduction of provisions of the organizational-economic mechanism of institutional modernization of the economy, including:

- Formation of civil society that will provide scientific, informational, and legislative support to the conscious elite of the state in the implementation of a state monitoring and accountability system for environmentally sustainable resource and energy consumption in enterprises, waste recycling, independent collection and systematization of economic, statistical, and other information.
- Establishment of partnership relations between the state and business, directing state power to support production facilities that implement management systems and efficient technologies, which will lead to a reduction in the consumption of all types of resources.
- Comprehensive socio-ecological-economic monitoring in the country and the introduction of preferential open market regulation of the consequences of innovation implementation in the field of standardization, development of directives, and codes in various areas of activity in economically developed countries.
- Improvement of the permit issuance legislation, approaching European directives and standards. Special attention is paid to consolidating the legislative foundations of resource-efficient and cleaner production rather than normative acts.
- Adaptation and implementation of a control and monitoring system for the state of the environment based on European indicators and standards, including the use of remote observation methods (e.g., percentiles of environmental indicators).
- Introduction of a registration and evaluation system for chemical substances to control the safety of raw materials and other materials, similar to the existing system in the EU as a Technical Regulation (Registration, Evaluation, and Authorization of Chemicals).
- Ensuring a financial mechanism for the targeted use of resource payments, particularly in the implementation of resource-efficient and cleaner production.
- Introduction of ecological passports for enterprises that have a negative impact on the environment.
- Reassessment of natural capital, revision of indicators and existing methodologies for calculating compensation for damages caused by violations of legislation on nature conservation and

rational use of natural resources, with the aim of compensating for such damages.

- Implementation of an environmental insurance mechanism for technologically hazardous facilities.
- Use of modern metrological support based on innovative methodologies and standards in nature conservation activities, monitoring the state of the economy, and the social sphere, among others.

CONCLUSION

To ensure support for macroeconomic reforms in the creation of an environmentally oriented and efficiently functioning market system, the establishment of a modern ecological information space, and the widespread integration in the nature-resource sphere, it is necessary to introduce the provisions of the methodology for preventive development of legislative and regulatory support through the modernization of organizational-economic, institutional, incentive, and socially responsible mechanisms, along with the corresponding socio-ecological-economic instruments of implementation (directives, codes, standards, etc.). At the same time, the process of developing regulatory documents should be transformed, primarily aimed at systematically addressing the socio-ecological-economic issues of Ukraine on the path to integration into the global eco-economic space.

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