DYNAMICS OF CLIMATE CHANGES AND ITS EFFECT ON THE PERFORMANCE OF CEREALS ACCORDING TO SATELLITE DATA

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Aim. To study the effect of climate changes on the performance of cereals. **Methods**. Remote, statistical, and analytic methods. Climate changes were determined by the sum of radiation temperatures of the earth's surface, calculated using the data of the infrared range (10.3–11.3; 11.4–12.4 μm) of the high precision radiometer AVHRR of the meteorological satellites of the Earth, NOAA. The effect of climate changes on the state of vegetation, including the phenological parameters, such as the beginning, the end, and the length of the vegetation period, was determined by the Normalized Difference Vegetation Index (NDVI) obtained using the data of infrared (0.72–1.1 μm) and red (0.58–0.68 μm) ranges of the abovementioned radiometer. The satellite data are openly accessed on the website of STAR NESDIS NOAA – Satellite Applications and Research of NOAA's National Environmental Satellite Data Information Services of the National Ocean and Atmosphere Research Department of the USA – http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/. The dynamics of CO_2 concentration in the air was determined using the satellite data of AIRS/Aqua (https://disc.gsfc.nasa.gov/datasets/AIRS3C2M_005/summary), the precipitation dynamics – using the data of ERA5 ECMWF/Copernicus Climate Change Service (https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#description). The association between the performance of cereals and satellite data was found by the method of correlation and regression analysis. **Results.** Using the satellite data, it was found that in 1982–2021, the sum of radiation temperatures of the earth's surface reliably increased in the vegetation period (April–September), and the amount of precipitation tended to decrease in the zones of Polissia, Forest-Steppe, and Steppe. The highest tempo of warming was observed in the territory of the Steppe. In general, the warming had a positive effect on the state of vegetation, according to NDVI, and on the performance of cereals. However, in the recent decade (2010–2020), the positive effect of the warming on the vegetation state decreased, and according to the NDVI trend, there has been a tendency towards the negative effect of the further increase in the temperature, which is especially remarkable for the Steppe and Forest-Steppe. On the contrary, the warming in the Polissia zone created the conditions for the increase in the performance of agricultural cereals. **Conclusions**. From 1982 till 2021, there was a strong tendency towards the increase in the sum of radiation temperatures of the earth's surface in the vegetation period and the decrease in the precipitation amount in Polissia, Forest-Steppe, and Steppe. According to the NDVI data, due to the warming, the length of the vegetation period increased by 14–21 days on average, which had a positive effect on the vegetation. Since 2010, the acceleration in the warming tempo has been observed. The average annual increase in the sum of the radiation temperatures of the earth's surface in the vegetation period is 15–16 °C – for Polissia, 14–18 °C for the Forest-Steppe, and 18–20 °C for the Steppe. According to this tendency, if the current regularity in the temperature increase in 1982–2021 is preserved in the nearest future, the temperature of the vegetation period will additionally increase, and the average sum of temperatures of the earth's surface will reach 4000 °C in Polissia, which was notable for the Forest-Steppe in 1982–2021, 4440–4600 °C – in the Forest-Steppe, and up to 5800–5900 °C in the Steppe. In 1982–2000, there was a strong regularity of the positive effect of the warming during the vegetation period both on the vegetation state according to the NDVI index, and the performance of cereals in all three natural climatic zones. However, after 2000, due to the negative effect of high summer temperatures on the crops, the effect of the warming on vegetation considerably decreased, which was especially notable for the Steppe where the increase in NDVI compared to the previous period was on average 9.41 % in 1992–2001, and in 2012–2021 – 1.78 %.

Key words**:** natural climatic zone, agroecosystem, satellite index, vegetation, temperature, precipitation, productivity, cereals, prognosis, performance.

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INTRODUCTION

The agroindustrial complex of Ukraine has a high agroresource potential and is an important producer and exporter of grain, ensuring the food safety of many countries. Therefore, it is important to investigate the regularities and risks related to regional climate changes and to forecast their effect on agrarian production, including cereals, in the near and distant future, which is relevant for the purposes of food safety planning and timely measures for adapting the agroecosystems to the warming. There is a climate monitoring system, which presupposes on-ground and remote observations. Noteworthy is the method of climate observations using satellite data about the temperature regime of the earth's surface, the conditions of moisture provision for the vegetation, the vegetation state, including the fields of crops, their development, and the manifestation of degradation processes in the agrolandscapes.

Agricultural production has rather complicated relations, regularities, and interactions of climatic and agrotechnical factors, which are becoming even more complicated and unpredictable due to the changes in the climatic system parameters. All this has a negative effect on the balance between all the components, which affects the formation of agroecosystem productivity. Temperature, moisture, and sunlight are the main factors for the growth of plants which can be illustrated using a relatively simple model CROPEVAL, where the weekly growth index (GI) is the product of three main climatic indices: light, temperature, and moisture: GI = LI × TI × MI (Nix, 1981). A series of publications by Ukrainian researchers have been dedicated to the study of the effect of some climate factors on specific components of the agroecosystems (Adamenko, 2014; Balabuh, 2019; Tararico et al, 2020; Polovyy et al, 2021).

There are many forecast estimates of the effect of climate changes on agriculture, which predict the increase or decrease in the performance of different crops, the disruption in the stability of food production, and enhanced drought phenomena (Wilson et al, 2021). The "climate-plant production performance" has two aspects: climate as one of the most important natural resources under optimal parameters, and climate as a risk for the productivity of agroecosystems under excessively high temperatures and moisture deficiency, which has a negative effect on photosynthesis. Thus, the research directions were formed considering the evaluation of the effect of slow changes in climate parameters in time on the agroecosystems and the effect of climatic extremes during the vegetation. Long-term changes in temperature or precipitation amount are less risky for agriculture than such extreme phenomena as droughts during the vegetation, severe frosts, soil erosion, and dust storms (Bolin, 1989).

Currently, due to the warming, there is a shift in the agroclimatic zones to the north, and, as a result, there is an extension of the areas of cultivating crops with a more extended vegetation period (Pysarenko et al, 2019). All these factors allow for cultivating sunflower and corn varieties of early and even late maturity in Polissia (Sobko et al, 2021). The performance of sunflowers in Polissia conditions is 2.3–2.38 t. (Savchuk et al, 2021). Under sufficient moisture provision in Polissia, the fields do not require watering, which reduces the expenses considerably. Yet, there are also negative aspects of expanding the fields of such intense crops as corn and sunflower on turf-podzolic soils with low humus content (Voropai H, 2020). The decrease of lupine, perennial grasses, and other forage crops in the structure of arable fields to the minimum leads to the imbalance of organic and biogenic matter in the crop rotations, which requires the application of a considerable amount of mineral fertilizers and liming. There is the intensification of the mineralization processes and the washing-out of organic matter, nitrogen, calcium, and other chemical elements from the soil, which has a negative effect on the physical-chemical properties and anti-erosion resistance of turf-podzolic soils. As a result, there are higher risks of erosion degradation and dust storms occurring on ever larger scales in the nearest future (Tarariko et al, 2017).

All the abovementioned demonstrates the urgency of the issue of monitoring the drought manifestation and its effect on vegetation, agricultural production, and food safety. In the territory of Ukraine, there are also additional internal factors promoting climate warming and the processes of desertification of the farming lands. First of all, it is related to the high ploughness of the agrolandscapes (up to 80–90 %), their rather low woodiness, high risk of moisture loss, and expansion of erosive degradation of soils under the decrease of soil-protective crops in the structure of arable soils and the increase in the volume of heavy precipitation (Tarariko et al, 2017).

To substantiate the strategy of developing agriculture and food safety, it is important to have systemic determination of the properties and tendencies in the direction of changes in agroclimatic resources. In this aspect, the determination and prediction of the tempo of climate warming, its effect on the shift in natural climatic zones, the transformation of the zonal systems of land use, the increase in the risks of manifestation of soil desertification and degradation processes, and the maintenance of high productivity of crops under these conditions are urgent issues. Such a wide spectrum of information on the global, regional, and local levels requires the use of agro-ecological monitoring and agricultural activity of the satellite informational resources in the system. Thus, *the aim* of our work was to investigate the effect of climate changes on the productivity of cereals using the satellite data.

MATERIALS AND METHODS

In terms of soil-climatic conditions, the territory of Ukraine belongs to three natural climatic zones. The Polissia zone is located in the north, from west to east; the specialization of agricultural production in it is directed at the cultivation of cereals, potato, flax, forage crops, and in recent years – corn and sunflower. The Forest-Steppe stretches from west to east, covering the central part of the country. The specialization of cultivating crops includes the production of cereals, sugar beet, sunflower, and forage crops. The specialization of agrarian production in the Steppe is related to the cultivation of cereals, sunflowers, and vegetables. The prevalence of chernozem soils with high fertility in the structure of the arable land and favorable climatic conditions promoted high effectiveness of agrarian production under relatively non-high expenditure of industrial resources. For this study, we chose the territory of the administrative regions of Ukraine with typical agroproduction, two in each natural climatic zone, which are located on the right bank and the left bank of the Dnipro, respectively. The average area of each region is about 25–30 thousand sq. km.

The climate changes and their effect on the vegetation state were determined using the available information from the satellite systems of low spatial resolution – multizonal advanced very high precision radiometers AVHRR and VIIRS of the meteorological polar-orbiting satellites NOAA, which make multispectral images of practically the entire surface of the earth twice a day in the ranges of 0.58–0.68; 0.725–1.1; 3.55–3.93; 10.3–11.3; 11.4–12.4 μm with the spatial resolution of 1.1 km and the width of the field of view of about 3,000 km. These data were obtained from the website of STAR NESDIS NOAA – Center for Satellite Applications and Research (STAR) of NOAA's National Environmental Satellite Data Information Services http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH. Using the data for the period from 1982 to 2021, we created maps or charts of the dynamics in temperature changes on the earth's surface during the vegetation period of each year in the scale of the regions under investigation according to the SMT index (Smoothed Temperature), where SMT is the weekly temperature of the earth surface, average in terms of regions; it is defined as the radiation temperature of the earth surface using the infrared data (10.3–11.3; 11.4–12.4 μm) (LSA SAF, 2010). To determine the vegetation state and to predict the effect of the warming on the productivity of cereals, we used the NDVI index (Normalized Difference Vegetation Index (Kogan, 2018). This index is a combination of spectral characteristics of the vegetation layer, and it is determined as

$$NDVI = (NIR–RED)/(NIR + RED),$$

where NIR and RED – the values for spectral brightness in the infrared (0.72–1.1 μm) and red (0.58–0.68 μm) ranges.

The result of climate fluctuations is seen in the changes in the conditions for the development and state of the vegetation, which can be investigated using multidimensional temporal and spatial analysis, including the change in the vegetation period. The characteristic of the length of the vegetation period mainly lies in determining its main parameters, i.e. the start and the end of the season and its length. For many years, the studies were based on traditional sources of information (i.e. direct observations combined with meteorological data). The dynamic development of technologies in recent decades allows for the application of properly processed satellite data with different temporal and spatial resolution. The start of season (SOS) is defined as a sharp increase in the intensity of spectral characteristics of the vegetation layer directly after a long period of photosynthesis rest (Zeng et al, 2020). At present, the SOS is mainly determined using the methods of remote probing, most frequently by the vegetation indices NDVI or EVI (Enhanced Vegetation Index), calculated by the obtained satellite data (Ba et al, 2022). During the vegetation period, these data are presented in the form of a smoothed curve. The term "SOS" indicates the beginning of the vegetation period and usually refers to the date of a considerable increase in NDVI values. However, different SOS values may be obtained from the time series, for instance, the moment in time when the NDVI values exceed a certain threshold or the moment in time when the curve starts going up (Siłuch et al, 2022).

Another phenological parameter, registered by the distance probing method, is the "end of season" (EOS) (Gao et al, 2020). It indicates the moment of an evident decrease in the values of specific phenological parameters for plants. "The length of the season" is most frequently defined as the length from the start (SOS) till the end (EOS) of the season. Some researchers also defined the "peak of season" as the date of maximal NDVI values. The plant vegetation period is determined using satellite data in open access, including MODIS, Landsat, AVHRR, and Sentinel-2 (Gao et al, 2020; Siłuch et al, 2022).

The dynamics of CO_2 in the territory of Ukraine during the period from January 2010 to February 2017 was determined using the satellite data of AIRS/Aqua (https://disc.gsfc.nasa.gov/datasets/AIRS3C2M_005/summary), and the dynamics of the precipitation from 1979 till 2020 – using the data of ERA5 of ECMWF/Copernicus Climate Change Service (https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#description).

The fields of the main crops and the dynamics of their performance in terms of administrative regions were determined by the data of the State Statistics Service of Ukraine in 1990–2021 and its association with NDVI – by the correlation regression analysis. To determine the effect of climate changes on the performance of corn and winter wheat on the local level, we used the results of the studies of the 1987–2017 permanent field experiment of the Poltava agricultural experimental station named after M. I. Vavilov, which was established in 1884 (geographical coordinates: 49°40' north latitude and 34°57' east longitude). The soil cover is medium-humus heavy-clay chernozem on loess (Kokhan et al, 2019, Zaryshnyak et al, 2016).

RESULTS OF INVESTIGATIONS

The effect of climate changes on the productivity of cereals was determined and predicted using satellite data, determining the mutual relations between the NDVI index, the average for the vegetation, and the performance of cereals. We found rather a close association between the average NDVI value for a certain time range of the vegetation period and the performance of cereals. In the Steppe, the dynamics of the performance in terms of years is in rather a close correlation with NDVI (Fig. 1). High correlation was found between the performance and the average NDVI value for the period from April 1 till June 1 which coincides with the start of the vegetation period and middle dough of awned cereals. The correlation between the average NDVI value for this period and the performance of cereals was from 0.65 in Polissia to 0.8 in the Steppe ($p < 0.05$).

The temperature during the vegetation period is one of the important climate factors affecting the vegetation state. There is a dependence between the average temperature of the earth's surface during the vegetation period in terms of each investigated administrative region and the average NDVI index, respectively. Fig. 2 presents the dynamics of the sum of radiation temperatures of the earth's surface (ST) for the vegetation period from 1982 till 2021 and NDVI, averaged for the vegetation period (NDVIa) in Polissia, the Forest-Steppe, and the Steppe, respectively.

The analysis of charts (Fig. 2) demonstrates that in Polissia, the Forest-Steppe, and the Steppe, the radiation temperature of the earth's surface during the vegetation period has increased in the last 38 years. It is noteworthy that according to the NDVI, the warming of the vegetation period from 1982 to 2021 had a positive effect on the vegetation state in the zone of Polissia and the Forest-Steppe. This regularity was manifested in the Steppe much less.

There was a considerable deviation in the temperature conditions from the tendency in terms of years which has been especially notable for the recent decade. On average, the sum of temperatures of the earth's surface during the vegetation period in 2012–2021 as compared to 1982–1991 increased in Polissia by 11–12 %, in the Forest-Steppe – by 12.0–13.0 %, and in the Steppe – by 14.0–16.0 %. The conclusion of the presented analysis may be that the highest tempo of the temperature in-

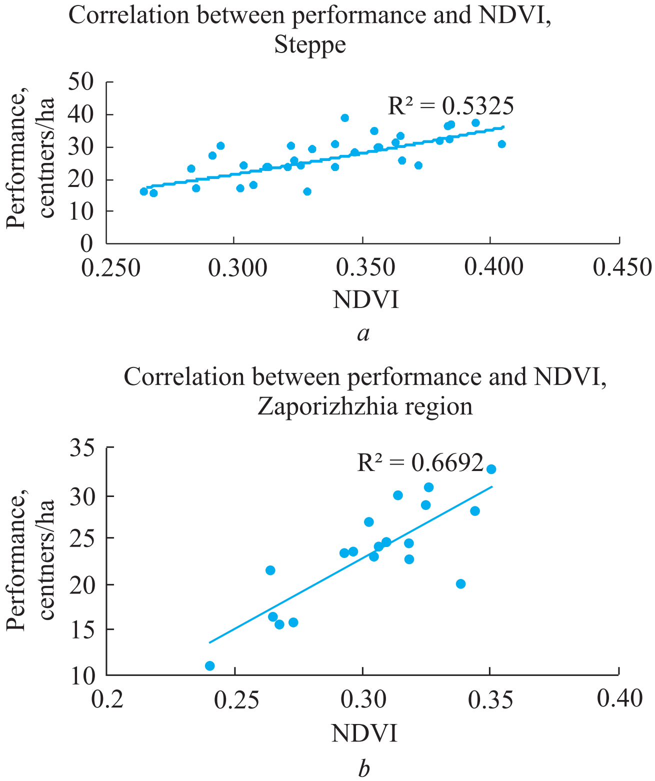

Fig. 1. The correlation between the NDVI index and the average performance of cereals: *a* – Steppe, *b* – Zaporizhzhia region

crease during the vegetation is observed in the Forest-Steppe and Steppe (Table 1).

According to the results of comparing the distribution for the sum of the radiation temperatures of the earth's surface during the vegetation period within the natural climatic zones in 1982–2000 and in 2000–2021, using spatial modeling for the temperature condition change, we determined the shift of aridity of natural climatic zones in the direction from south to north. Therefore, there is an extremely urgent issue of mitigating the negative consequences of climate warming and elaborating the differentiated systemic measures in adapting the zonal agroecosystems to climate changes.

Regardless of some dry years, in general, the tendency of the two recent decades is for the warming of the vegetation period to have a positive effect both according to the NDVI indices and the performance of cereals in Polissia, the Forest-Steppe, and the Steppe. Thus, in general, for the period of 1982–2021, the climate change in the territory of Ukraine had a positive effect on the state and productivity of zonal agroecosystems. As for the vegetation state, it may be noted that gradually, starting from 2001, the positive effect of the warming on the vegetation according to the NDVI decreases, which is especially notable for the Steppe, in the territory of which there usually were high risks of drought phenomena which may be enhanced. Thus, starting from 1982, the positive effect of the warming in this zone is manifested much less or not manifested as compared to Polissia and the Forest-Steppe.

To determine the tempo of the temperature increase and its effect on the vegetation state according to the NDVI index, the time period from 1982 to 2021 was divided into four ten-year-long periods. We found the period of relative slowing down of the warming (1992–2001) and subsequent acceleration of the tempo for the increase in the sum of radiation temperatures of the earth's surface during the vegetation period, starting from 2002 in all the natural climatic zones (Table 1).

There was a respective response of the vegetation to the warming according to the NDVI (Table 2). In the second decade (1992–2001), on average during the vegetation period as compared to the first one (1982–1991) the NDVI index in Polissia, the Forest-Steppe, and the Steppe increased on average by 7.6–9.2 %, in the third decade (2002–2011) – by 3.5–4.8 %, and in the fourth one – only by 1.7–1.8 %. The obtained results demonstrate an ever lower positive effect of a further increase in the radiation temperature of the earth's surface during the vegetation period on the vegetation state according to the NDVI index, which is especially notable for the Steppe, where rather a high variability in this index is observed in terms of years. If this regularity is preserved in the following decades, one may expect its further decrease due to the manifestation of more intense drought phenomena.

One of the positive effect factors of the warming on the vegetation state and performance of cereals, especially in Polissia and the Forest-Steppe is the extension of the vegetation period, which is determined using the comparison of 1982–2001 and 2002–2021.

The length of the vegetation period in terms of regions and natural climatic zones was determined by the dynamics of the perennial NDVI value during the vegetation period, which is presented in the form of a smoothed curve (Fig. 3). Since usually in Ukraine at the start of the vegetation season, the NDVI values do not exceed 0.2 with its gradual increase up to 0.3–0.8, and by the end of the vegetation period, decrease down to 0.2, we defined SOS and EOS parameters to be the dates when the NDVI curve reached these values during the increase and decrease, respectively. The analysis demonstrated that in the two recent decades,

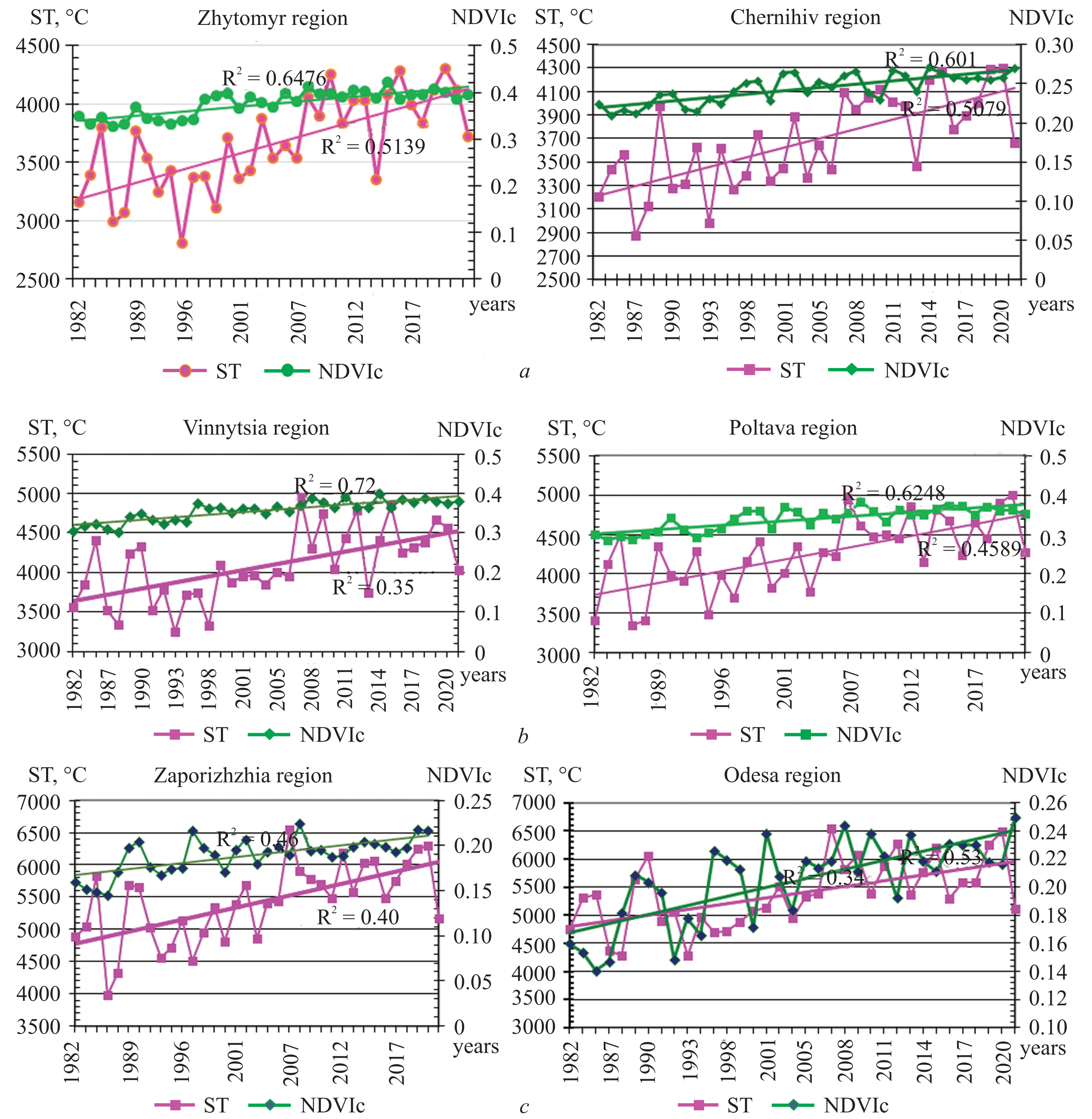

Fig. 2. The dynamics of the sum of the radiation temperatures of the earth's surface in the vegetation period and NDVI for 1982–2021: *a* – Polissia (Zhytomyr and Chernihiv regions), *b* – Forest-Steppe (Vinnytsia and Poltava regions), *c* – Steppe (Zaporizhzhia and Odesa regions)

as compared to the two previous ones, the vegetation period in Polissia started 14 days sooner. In the Forest-Steppe, there is an earlier start of vegetation – up to 7–14 days sooner, and in the Steppe – up to 14–21 days sooner (Fig. 3). Therefore, according to the NDVI index, in recent 20 years, there is a tendency towards the increase in the length of the vegetation period by 2–3 weeks on average, mostly due to the earlier start and later end of the vegetation period which is especially notable for Polissia and the Forest-Steppe. The extension of the vegetation period is one of the factors of more effective use of the conditions for autumn vegetation of winter crops which had a generally positive effect on the vegetation state according to the NDVI and the yield of cereals, especially notable for Polissia and the Forest-Steppe. At the same time, the increase in the temperature background in spring, due to the increase in its dryness, had a negative effect on the productivity of early cereals (Balabukh, 2017).

An important factor in improving the vegetation state according to the NDVI and the performance, including cereals, is also an increase in the content of CO_2 in the air according to the climate models (Norton R, 2012), which has a positive effect not only on the photosynthesis productivity but also on more efficient use of moisture by plants (Miroshnichenko M, 2016; Demydenko O, 2015). According to the experimental studies of R. Norton et al (2012), the gain in wheat harvest due to the increase in the concentration of CO_2 in the air from 385 ppm to 550 ppm is from 0.5 to 0.9 t/ha in a dry year and a year with normal moisturization, respectively. Fig. 4 presents the dynamics of the increase in the concentration of CO_2 in the atmosphere. As seen, from 2010 till 2017, the content of CO_2 in the air increased from 385–390 to 400–405 ppm, which is also a positive effect factor of photosynthesis productivity and performance of crops on the condition of soil fertility state, close to the optimal one, and moisture provision for the plants.

The conditions of moisture provision for the vegetation depend on the precipitation amount and are vital for the formation of the performance of crops, including cereals, especially under climate warming. The average annual amount of precipitation during the period of studies fluctuated greatly in different years, which

Table. 1. The sum of the radiation temperatures of the earth's surface in the vegetation period (April–September) in some decades

Region	Period			
	1982–1991	1992–2001	2002–2011	2012–2021
Polissia				
Zhytomyr	3371	3327	3853	3985
Chernihiv	3347	3427	3841	4020
Forest-Steppe				
Poltava	3879	3985	4405	4602
Vinnytsia	3847	3717	4250	4401
Steppe				
Zaporizhzhia	5052	4926	5644	5882
Odesa	5084	4852	5652	5792

Table 2. The NDVI dynamics during the vegetation period (April–September) in some decades

Region	Period			
	1982–1991	1992–2001	2002–2011	2012–2021
Polissia				
Zhytomyr	0.342	0.369	0.392	0.398
Chernihiv	0.337	0.363	0.376	0.390
Forest-Steppe				
Poltava	0.304	0.332	0.353	0.361
Vinnytsia	0.324	0.350	0.370	0.378
Steppe				
Zaporizhzhia	0.255	0.284	0.286	0.283
Odesa	0.256	0.288	0.306	0.310
NDVIav	0.303	0.332	0.347	0.353
NDVI gain, % to previous		9.41	4.73	1.78

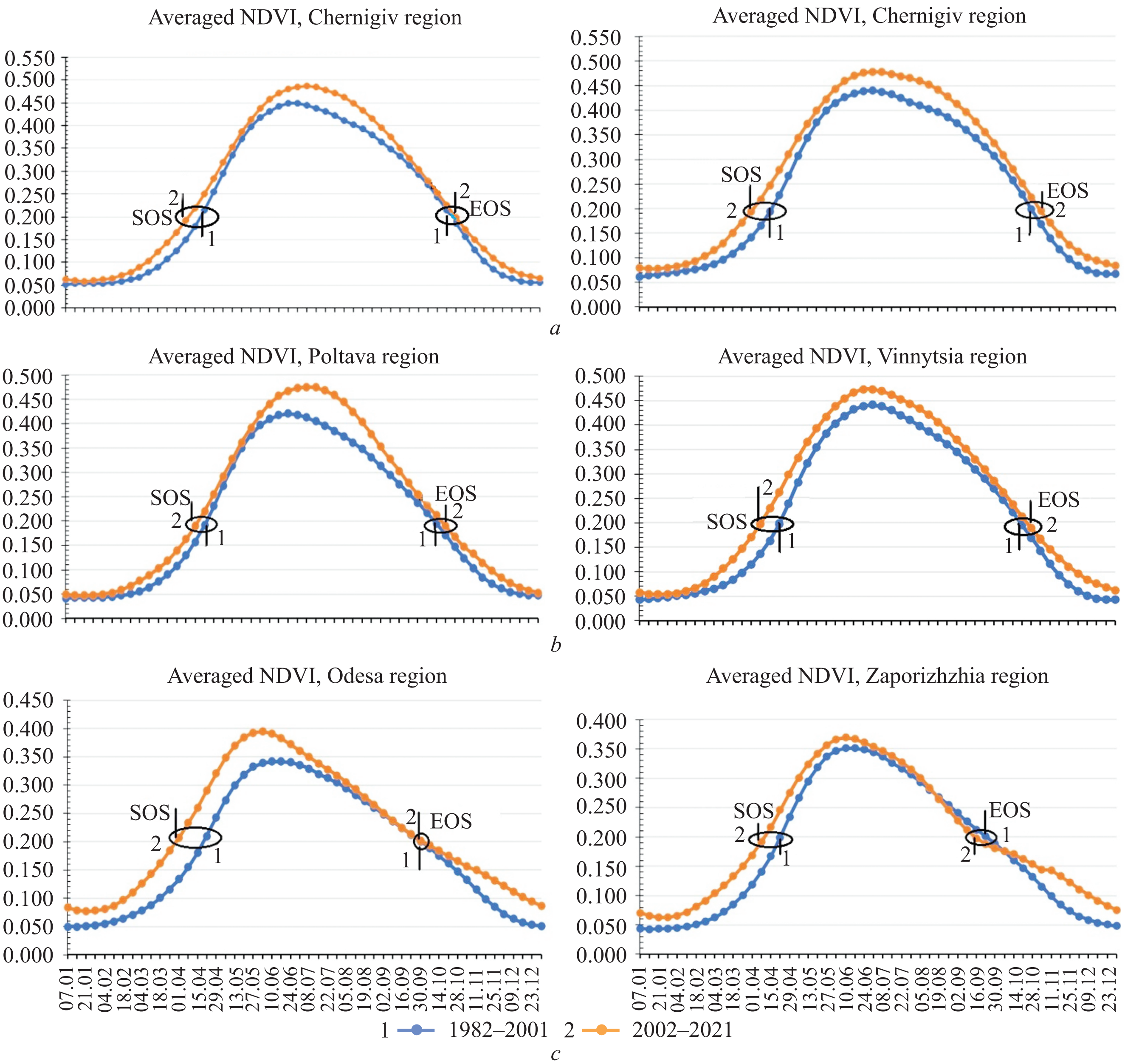

Fig. 3. The comparative annual dynamics of the average values of NDVI for 1982–2001 and 2002–2021: *a* – Polissia, *b* – Forest-Steppe, *c* – Steppe

generally determined the productivity of crops. Starting from 1979, the satellite data demonstrate a tendency towards the formation of a declining tendency for the total amount of precipitation for the year. The tendency of a decrease in the annual amount of precipitation in the recent twenty years (2000–2021) is preserved and even increased as compared to the previous period (1979–1999) (Fig. 5). For instance, in Polissia, the Forest-Steppe, and the Steppe the amount of precipitation decreased by 130 mm, 200 mm, 160 mm within the period of 1979–1999 respectively; at the same time, within the following period (2000–2021) it increased additionally up to 180 mm, 250 mm, 260 mm. Under increasing temperatures of the vegetation period, there are higher moisture losses due to evaporation which conditions the occurrence of deeper drought phenomena in all the natural climatic zones but even more so – in the Steppe.

So, Ukraine's climate has changed considerably in the recent 40 years. There has been a temperature increase and thus, the prolongation of the vegetation period, the deterioration of moisture provision, the expansion of aridization and desertification processes, and the shift in natural and climatic zones.

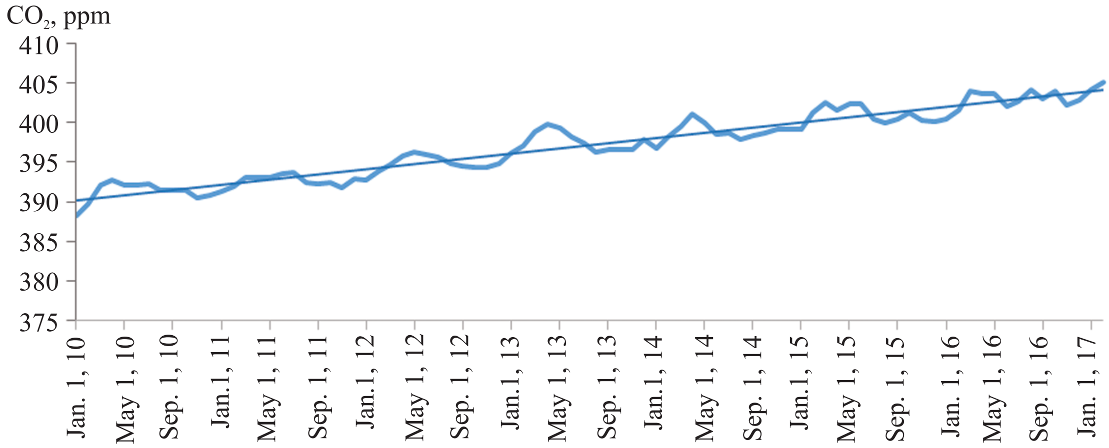

Fig. 4. The dynamics of CO_2 concentration in Ukraine's atmosphere according to the satellite data of AIRS/Aqua (https://disc.gsfc.nasa.gov/datasets/AIRS3C2M_005/summary)

Yet agrarian production adapted to climate warming rather fast, for instance, in Polissia and the northern regions of the Forest-Steppe, where the additional heat resource is used to correct the structure of the arable fields with the purpose of expanding the areas of the crop fields with the longer vegetation period, including corn and sunflower. In the 1990-s, the area of corn fields in Polissia was insignificant, but in 2018–2019, this crop was grown on up to 1,200 thousand ha, and the area of sunflower fields increased from a hundred hectares to 500–600 thousand ha. The same is true for the Forest-Steppe, where the areas of corn and sunflower fields continue enlarging up to 1,800 and 560 thousand ha, respectively. On the contrary, in the Steppe, the area of corn fields decreased considerably and got stabilized at the level of 1,000–1,100 thousand ha, mostly only under watering (Fig. 6). The area of sunflower fields as a more drought-resistant crop, continues enlarging in this zone, and amounts to 3,700–3,800 thousand ha (the State Statistics Service of Ukraine, 2021).

A current system of evaluating the resource capabilities of Ukrainian soils involves their qualitative estimation by the natural potential of soil and the agrosoil potentials of natural and effective fertility. While the agropotential of natural fertility reflects the productivity of the crops based on natural resources of soil (absolute control), the agropotential of effective fertility also involves fertility after the introduction of optimal doses of fertilizers and ameliorants. In Ukraine, these conditions are met only by the performance data of the leading crops (determined in long-term permanent experiments (up to 40 and more years) which were grown after the 1960-s: the varieties and hybrids of intense type (Polupan M, Velychko V, 2019)). The performance results of the agrocrops were adjusted with the consideration of the climatic parameters during the study years to their average annual values (Velychko, 2010).

The consideration of the mutual relations established between the main agricultural factors and the climatic conditions of their effect on the soil fertility and crop performance due to the implementation of the corresponding specialization system, taking into account the natural fertility of soils at the beginning of the 2000-s, allowed for our estimating (predicting) the parameters of agrosoil potentials for the agroproduction in Ukraine in the amount of 41.7 million cereals and grain legumes, 3.6 million – of sunflower, and under effective fertility – 54.2 and 4.1 million tons respectively (Polupan et al, 2005).

In recent decades, there are evident climate changes in the world, including Ukraine, which have their effect on the productivity of cereals too. In these conditions, the selection of crops with the consideration of their adaptive possibilities and the state of soil resources may ensure a stable perennial harvest of agricultural products. The implementation of the zonal system of specialization for Ukraine's territories with the consideration of climatic realities allows for obtaining the basic average annual gross harvest of cereals and grain legumes of 51.2 million tons under natural fertility and 63.6 million tons under effective fertility, and 33–39 million tons of sunflower, respectively. These amounts of gross production may change according to the fluctuation of weather and climate conditions on average by ± 10–20(25) % (Polupan et al, 2015).

It is important to investigate the effect of the gradual warming of the climate time-wise according to the NDVI index not only on the vegetation state but also on the harvest of cereals, in particular.

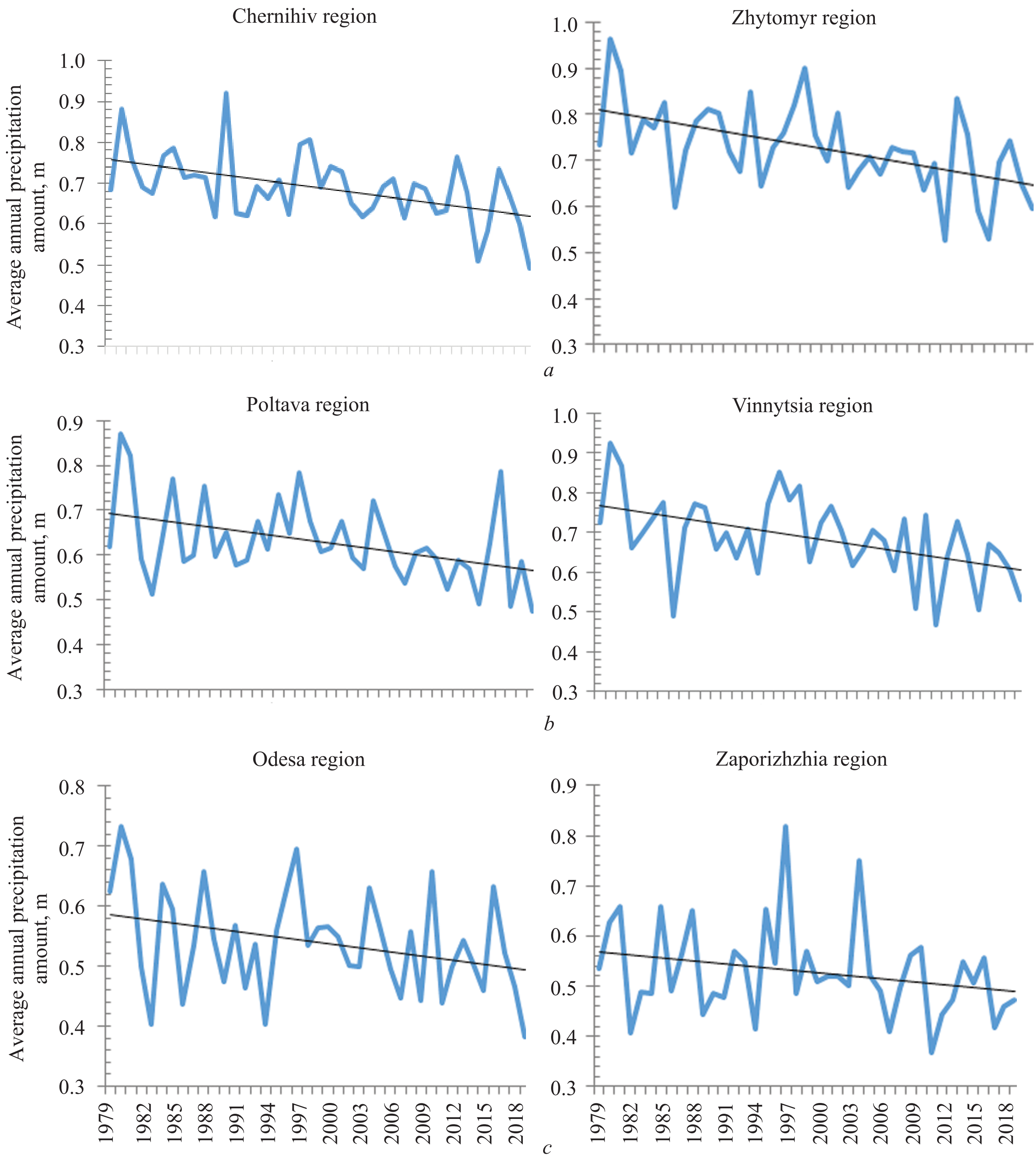

Fig. 5. The dynamics of the annual amount of precipitation according to the data of ERA5 ECMWF/Copernicus Climate Change Service (https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#description): *a* – Polissia, *b* – Forest-Steppe, *c* – Steppe

In general, at the level of the agroindustrial complex of Ukraine, both the satellite data and the official statistics demonstrate the positive effect of climate warming on the performance of cereals, especially corn, which before 2020–2021 ensured the gross harvest of cereals at the level of 75 million tons of grain and its export in the amount of up to 40–45 million tons (Fig. 7).

It should be noted that this achievement has become possible due to the expansion of the arable fields with corn, the productivity of which reached and even ex-

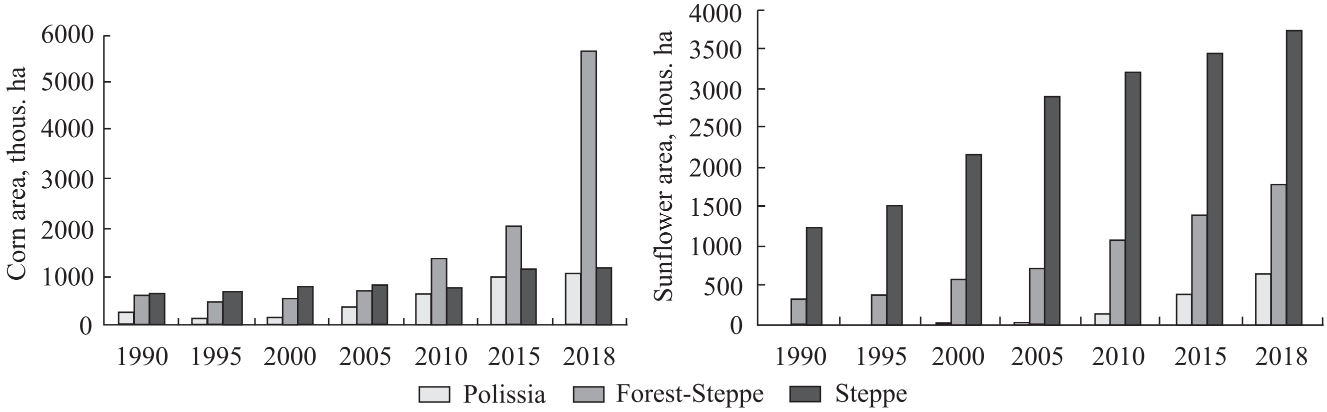

Fig. 6. The dynamics of the areas of corn fields for grain and sunflower in terms of natural climatic zones of Ukraine

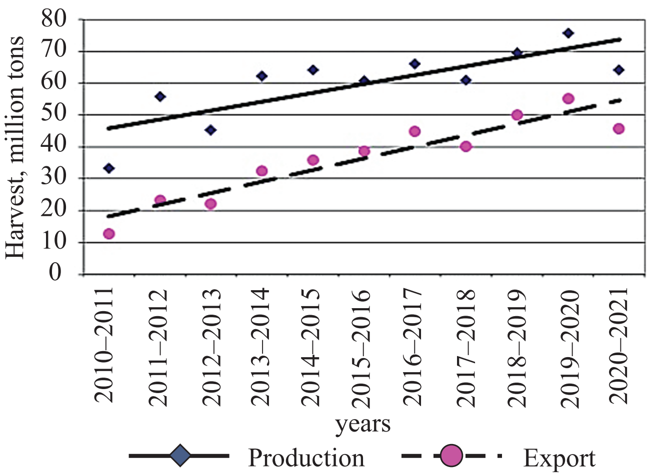

Fig. 7. The dynamics of grain production and its export from Ukraine in 2010–2021, million tons (according to the data of USDA)

ceeded 100 centners/ha in 2021, according to the data of the State Statistics Service.

DISCUSSION

According to the data of the Ministry of Environment and Natural Resources of Ukraine, since the beginning of the 20th century, the average annual air temperature has increased by 2.0 degrees, including an increase by 1.2 degrees in the recent 30 years (Müller, 2016; Wilson, 2021). The highest tempo of the warming was noted in 2015–2020, the last of these years was the warmest, and the meteorological winter did not start in a considerable territory that year. These changes in the temperature conditions affected the development of cereals. Their productivity greatly depends not only on the air temperature during the vegetation period but also on moisture provision for the plants. In case of any deviations in the temperature conditions and moisture provision conditions from the optimal values, there was a considerable decrease in photosynthesis productivity (Dmytrenko, 2010). But in some natural climatic conditions, climate warming may promote the increase in the performance of such crops as corn, winter wheat, and soybeans under optimal moisture provision (Wilson, 2021). Therefore, it is important to conduct timely monitoring of the warming and the moisture content in soil pertaining to natural climatic specificities of the region, a specific crop rotation, and the field, which opens additional possibilities for early prevention of critical phenomena and relevant adjustment of the technologies of cultivating some crops.

The data and forecast estimates regarding climate changes in the territory of Ukraine, conducted by the National meteorological service of the UK using modern climate models, were extremely interesting (Wilson, 2021). It was found that in the recent 30 years, the air temperature in Ukraine increased by 1.5 degrees, and the tempo of warming was higher as compared to the neighboring countries in the recent decade. No increase in the amount of precipitation was registered. Thus, the increase in the temperature will promote additional moisture expenditure for non-productive physical evaporation, which will thus increase the risks of drought phenomena not only in the Steppe but also in the northern and north-eastern regions of the Forest-Steppe and even Polissia. It was also noted that the number of years with warm winters is growing, and the years with cold winters are either fewer or not registered at all (Wilson, 2021). Among the negative consequences of the warming, there is not only the manifestation of drought phenomena but also more extreme climate, for instance, the increase in the amount of summer heavy precipitation and wind conditions in spring which increases the risks of water and wind erosion of soils (Huo, 2021).

At present, the most common method of predicting climate changes is the use of rather complicated climate models, which consider the interaction between the oceans and atmosphere and different concentrations of greenhouse gases in the atmosphere (Stocker et al, 2015). According to their results, it was found that the consequences of the warming may be more significant than had previously been believed (Palmer, 2021). According to current climatic scenarios of moderate (RCP4.5) and high (RCP8.5) concentrations of greenhouse gases, it is expected that up to 2050, the average air temperature in Ukraine's territory will increase by 1.2–3.0 degrees respectively (Krakovska et al, 2021). The prediction demonstrates the probability of a decrease in the amount of summer precipitation or its preservation at the current level, which may enhance droughts and their negative effect on agriculture (Wilson, 2021).

Due to the warming, the territory with a considerable moisture deficiency for the period of 1991–2016 as compared to 1901–1990 was enlarged by 7 % and now covers up to 30 % of Ukraine's territory or about 11,0 million ha of arable lands. Obviously, this transformation of climatic conditions has had rather a radical effect on plant production, first and foremost, including the spatial location of such intense crops as corn and sunflower. According to the data of the National Institute of Strategic Research, cereals covered about 45–46 % of arable fields in the Steppe. However, it is merely 35 % of the total grain production. The decrease in the gross harvest of cereals in this zone is conditioned by the fact that the average performance of cereals in the recent five years has decreased from 35.8 centners/ha in 1990 down to 32.9 centners/ha in 2013–2017 (Wilson, 2021). At the same time, in Polissia and the Forest-Steppe, the performance of cereals has increased from 30.0–37.0 centners/ha to 48.0–53.0 centners/ha. In general, the average performance of cereals and grain legumes in these zones has increased by 46–61 % since 1990, and in the Steppe, it decreased by 10 % (Müller, 2016).

The results of the field studies conducted in 1985–2018 on the permanent field of the Institute for Agriculture of Western Polissia, the NAAS (coordinates: 50°12' north latitude, 26°29' east longitude) (Zaryshnyak et al, 2016) demonstrate a considerable improvement in heat supply for the agroecosystems, including a stable increase in the sums of effective temperatures above 10 °C. It created favorable conditions for the cultivation of thermophilic crops, such as corn, soybeans, and sunflower, in the north-western Forest-Steppe. As these crops are spreading fast now, the structure of the arable fields and agrolandscapes of the region have become quite similar to the southern Right-Bank Forest-Steppe (Polovyy et al, 2021).

The change in the air temperature, the amount of precipitation and their combined effect on the productivity of crops as well as the change in the fruitfulness of the climate in the current climatic period (1981–2010) and their probable changes up to the middle of the 21st century (2021–2050) using the scenario of SRES A1B (Nakicenovic et al, 2000) were analyzed in detail pertaining to winter wheat (Balabukh et al, 2017) and corn (Balabukh, 2019).

For instance, it was shown that in Polissia, the changes in the air temperature as compared to the current climatic period in different phases of winter wheat development might fluctuate from 0.5 °C (milk-wax ripeness) by up to 1.5°C during the seasons of sowing, germination, and end of vegetation (Malytska and Balabukh, 2020). In general, according to the cumulative coefficient of productivity, the cultivation conditions for winter wheat in Polissia will remain satisfactory by scenario A1B in the middle of the 21st century.

In the Forest-Steppe, the air temperature will continue rising from west to east during the entire vegetation cycle until the middle of the 21st century. The most significant changes are expected during autumn vegetation and in winter, when it stops and may exceed 1.5 °C. Due to these changes, the thermal conditions for the cultivation of wheat will become favorable during the entire vegetation cycle, while in the current climatic period, they were satisfactory in the eastern Forest-Steppe. There is a forecast of insignificant changes in the precipitation amount; their amount will be satisfactory for the cultivation of winter wheat almost in the entire Forest-Steppe. Thus, it is predicted that until the middle of the 21st century, the cultivation conditions of winter wheat in the Forest-Steppe might remain satisfactory and similar to the current climatic period (Malytska and Balabukh, 2020). The greatest changes in the thermal conditions (exceeding 0.8–1.9 °C) within the vegetation cycle of wheat cultivation are expected in the Steppe.

The greatest changes (the increase in the air temperature by 1.7–1.9 °C) are expected in the southern Steppe, which will lead to a considerable deterioration in the conditions of its cultivation from satisfactory to unsatisfactory (Malytska and Balabukh, 2020). The result of it is a probable decrease in the performance of winter wheat down to 10–13 % in the southern Steppe. The change in the amount of precipitation in the entire territory of the Steppe for almost the entire vegetation cycle of cultivating winter wheat may be insignificant until the middle of the 21st century and will mostly decrease. Therefore, the increase in the air temperature and the change in the moisturization conditions, observed during the vegetation cycle of winter wheat cultivation in the current climatic period, will be observed until the middle of the 21st century and may have a negative effect on its performance, especially in the south of the country. However, according to the scenario A1B, the agrometeorological conditions of cultivating this crop will remain favorable and satisfactory in the entire territory of the country (Balabukh et al, 2017).

The changes in the length of the vegetation period are also related to the climate changes which affect the state and productivity of agroecosystems. The extension of the vegetation period length promoted the diversification of crops or the possibility of collecting harvest several times in one season. On the other hand, it may result in a reduction in the set of crops. For instance, the studies conducted in China (Li et al, 2022) demonstrated that the changes in temperature and moisturization conditions in 2000–2019 in the territory of Qilian Mountains (Qilian Shan, a mountain range on the border of provinces Qinghai and Gansu, west-central China) resulted in the changes in the length of the vegetation period for pastures. According to the vegetation index of NDVI, it was found that the SOS in most regions, except for the north-west mountainous region, was 5–20 days sooner, and the EOS was delayed in the north and southeast by more than ten days, and in the northwest and the central part of the territory under investigation, it started 5–20 days sooner. Thus, the length of the vegetation season (LOS) in the southeast was 20–40 days longer, and in the northwest – 10–30 days shorter.

Similar studies were conducted to determine the effect of climate on the phenological indices of gum elastic in Southern Sumatra, Indonesia from 2010 till 2019. It was shown that the phenological SOS, EOS, and LOS were closely related to such deviations as extreme precipitation and increased temperature. The increase in the temperature by 1 °C led to an increase in SOS by ~25 days and EOS – by ~14 days (Azizan, 2021).

It is also important to investigate the effect of the gradual warming time-wise according to the NDVI index not only on the vegetation state but also on the harvest of cereals in the controlled conditions of classic field experiments. In this respect, extremely relevant are the results of perennial studies conducted in 1994–2017 during the permanent field experiment of the Poltava State Agricultural Experimental Station named after M.I. Vavilov, the Institute of Swine Production and Agroindustrial Production, the NAAS of Ukraine (Kokhan et al, 2019). The 7-field crop rotation was used to study the interaction of different technological ways of cultivating the crops and their effect on soil fertility, and the use of moisture resources, including the effect of climatic factors on the yield and quality of the products (Kokhan et al, 2019).

To determine the dynamics of the changes in the climatic factor and its effect on the productivity of cereals, in this experiment, we selected the control variant of the experiment (without fertilizers) i.e. on the background of the natural fertility of soil. Thus, the dynamics of the yield in terms of years depended only on the temperature conditions of the vegetation period and natural conditions of moisture provision (Fig. 8, *a*, *b*, *c*).

Fig. 8, *a* demonstrates that under the natural fertility of typical chernozem and typical technology of crop cultivation, starting from 1987, the performance of corn increases which correlates with the increase in the radiation temperature of the earth's surface during the vegetation period and NDVI (Fig. 2, *b*) under the same conditions of moisturization in Poltava region. A similar trend is observed for winter wheat as well, but the growth tempo is slower. There is rather high productivity at the level of 4–6 t/ha for corn and 3–5 t/ha for winter wheat without the introduction of fertilizers and pesticides, and the variability of performance in terms of years is mainly related to the moisture provision conditions. Other regularities were obtained for awned cereals, including barley, the productivity of which, on the background of the natural fertility of soil, decreased according to the tendency (Fig. 8), which may be associated with the increase in the air temperature in spring months by 1.6–3.3 °C, and in summer months – by 1.9–2.4 °C as compared to the perennial indices. In this case, in spring, the amount of precipitation changed by 13 %, and in summer – by 25 % (Kokhan et al, 2019).

All the abovementioned leads to the conclusion that the satellite retrospective and urgent information is an efficient instrument for observations and predictions of climate changes in space and time, as well as their impact on agroecosystems. The obtained satellite data and regularities related to climate warming are rather close to the results, obtained by the climatic models (Wilson, 2021). Modern systems of satellite observations ensure high spatial specification of the information about the change in climatic parameters and their effect on the

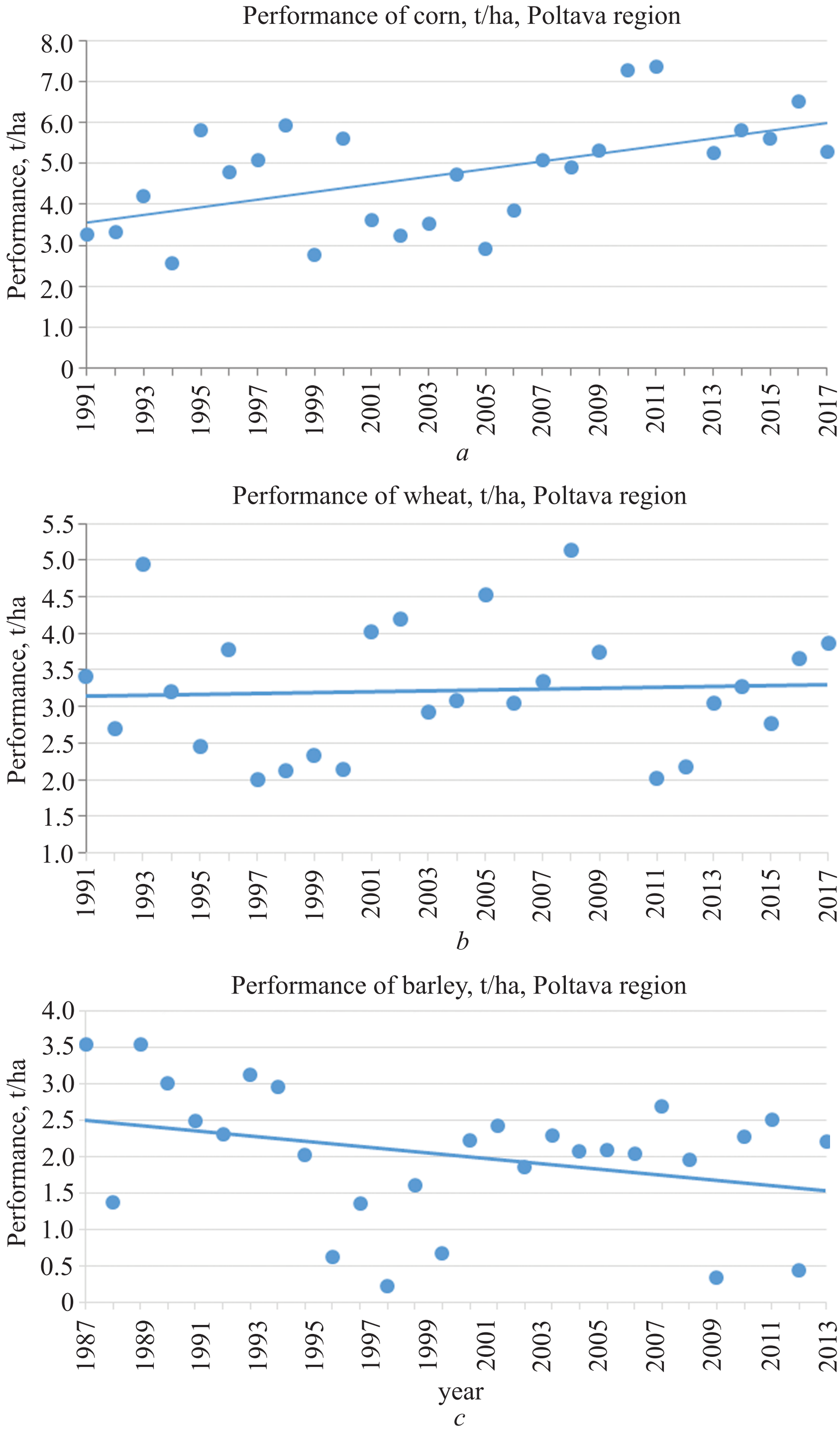

Fig. 8. The performance of corn (*a*), winter wheat (*b*) and spring barley (*c*) in the permanent field experiment of the Poltava State Agricultural Experimental Station (control variant)

state of vegetation and productivity of cereals, in particular. Thus, it would be reasonable and promising to involve the satellite informational resource in the system of agroecological monitoring, predicting climate changes, and evaluating its effect on the productivity of the crops.

CONCLUSIONS

According to the satellite data for the period of 1982–2020, there was an increase in the sum of radiation temperatures of the earth's surface during the vegetation period (April–September) on average for the year: in Polissia – 15–16 °C, in the Forest-Steppe – 14–18 °C, and the Steppe – 18–20 °C. There is a tendency toward the accelerated warming of the vegetation period from 2010 to 2021. If the current regularity in the warming is preserved in the nearest future, the temperature of the vegetation period in Polissia, the Forest-Steppe, and the Steppe may additionally increase, and the sum of temperatures of the earth's surface during the vegetation period will reach up to 4000 °C in Polissia which was notable for the Forest-Steppe in 1982–1990, 4440–4600 °C to in the Forest-Steppe, and up to 5800–5900 °C in the Steppe.

In 1982–2000, there was a strong regularity of the positive effect of the warming during the vegetation period both on the vegetation state according to the NDVI index and the performance of cereals in all three natural climatic zones. However, after 2000, due to the negative effect of high summer temperatures on the crops, the positive effect of the warming on vegetation is considerably decreased, which is especially notable for the Steppe, where the increase in NDVI compared to the previous period was on average 9.41 % in 1992–2001, and in 2012–2021 – 1.78 %. Due to the warming, the length of the vegetation period increased by 7–21 days on average, which had a positive effect on the vegetation state according to NDVI and on the performance and gross yields of cereal crops, especially in Polissia and the Forest-Steppe.

Climate warming will require further elaborations and improvement of differentiated systemic measures regarding soil and climatic conditions to adjust the zonal agroecosystems to climate warming on the state, regional, and local levels. In this respect, it is relevant to introduce urgent and retrospective satellite information into the system of agroecological monitoring with the purpose of improving the integrated management of ground, water, and biological resources, predicting and strategic planning of agrarian production, and food safety.

Compliance with ethical standards. No experiments, described in this article, involved animals.
Conflict of interest. The authors declare the absence of any conflict of interest.
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Динаміка змін клімату та його вплив на продуктивність зернових культур за супутниковими індикаторами

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Мета. Дослідити вплив змін клімату на продуктивність зернових культур**. Методи**. Дистанційні, статистичні, аналітичні. Зміни клімату визначали за сумою радіаційних температур земної поверхні, розрахованих за показниками інфрачервоного діапазону (10.3–11.3 мкм; 11.4–12.4 мкм) високоточного радіометра AVHRR метеорологічних штучних супутників Землі NOAA. Вплив змін клімату на стан рослинності, зокрема визначення фенологічних параметрів, таких як початок, кінець і тривалість вегетаційного сезону, за нормалізованим диференційним вегетаційним індексом (NDVI – Normalized Difference Vegetation Index), отриманих за даними інфрачервоного (0,72–1,1 мкм) і червоного (0,58–0,68 мкм) діапазонів вище наведеного радіометра. Супутникові дані знаходяться у відкритому доступі на сайті STAR NESDIS NOAA – Satellite Applications and Research of NOAA's National Environmental Satellite Data Information Services – Центру використання супутників і досліджень Національної служби супутникових даних та інформації Національного управління по дослідженням океану та атмосфери США – http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/. Динаміку концентрації CO_2 у повітрі визначали за супутниковими даними AIRS/Aqua (https://disc.gsfc.nasa.gov/datasets/AIRS3C2M_005/summary), динаміку опадів за даними ERA5 ECMWF/Copernicus Climate Change Service (https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#description). Зв'язок урожайності зернових культур із супутниковими індикаторами визначали методом кореляційно-регрессійного аналізу. **Результати.** За супутниковими даними встановлено, що за період з 1982 по 2021 роки сума радіаційних температур земної поверхні за вегетаційний період (квітень – вересень) закономірно підвищувалась, а кількість опадів, навпаки, мала тенденцію до зменшення в зонах Полісся, Лісостепу та Степу. Найвищі темпи потепління спостерігали на території степової зони. Потепління в цілому позитивно впливало як на стан рослинності за NDVI, так і на продуктивність зернових культур. Але за останнє 10-річчя (2010–2020 рр.) позитивний вплив потепління на стан рослинності зменшився і навіть у перспективі за трендом NDVI намітилась тенденція негативного впливу подальшого підвищення температури, що особливо характерно для зони Степу і Лісостепу. В зоні Полісся, навпаки, внаслідок потепління створились умови для підвищення продуктивності зернових сільськогосподарських культур. **Висновки.** За період з 1982 по 2021 роки спостерігали стійку тенденцію підвищення суми радіаційних температур земної поверхні вегетаційного періоду та зменшення кількості опадів у зонах Полісся, Лісостепу і Степу. За даними NDVI, внаслідок потепління, тривалість вегетаційного періоду в середньому збільшилася на 14–21 день, що позитивно впливало на рослинність за NDVI. Відмічається прискорення темпу потепління починаючи з 2010 р. Підвищення суми радіаційних температур земної поверхні за вегетаційний період у середньому за рік становив: для зони Полісся – 15–16 °C, Лісостепу – 14–18 °C і Степу – 18–20 °C. За трендом при збереженні існуючої закономірності підвищення температури за період 1982–2021 рр. у ближній перспективі температура вегетаційного періоду ще додатково підвищиться і сума температур земної поверхні в середньому досягне в зоні Полісся 4000 °C, що було характерно для зони Лісостепу за період 1982–2021 р., у зоні Лісостепу – 4440–4600 °C, у зоні Степу – до 5800–5900 °C. Впродовж 1982–2000 рр. спостерігали стійку закономірність позитивного впливу потепління вегетаційного періоду на стан рослинності як за показником NDVI так і врожайністю зернових культур у всіх трьох природно-кліматичних зонах. Але після 2000 р., унаслідок негативного впливу високих літніх температур, позитивний вплив потепління на рослинність значно зменшується, що особливо характерно для зони Степу, де збільшення NDVI до попереднього періоду становило в середньому 9,41 % у 1992–2001 рр., а в 2012–2021 рр. – 1,78 %.

Ключові слова: природно-кліматична зона, агроекосистема, супутниковий індикатор, рослинність, температура, опади, продуктивність, зернові культури, прогноз, урожайність.

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