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IMPACT OF CLIMATE CHANGES ON AGRORESOURCES OF UKRAINIAN POLISSIA BASED ON GEOSPATIAL DATA

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Aim. To determine the patterns of the climate change impact on the transformation of agricultural production and the ecosystem of Ukrainian Polissia in terms of time and space. **Methods.** Satellite and statistical data for the last 40 years (1982–2022) were used. The mean temperature for the vegetation period was defined by the sum of radiation temperatures of the terrestrial surface, calculated using the data of the infrared range (10.3–11.3; 11.4–12.4 µm) of the high-precision AVHRR radiometer of artificial meteorological Earth's satellites, NOAA, and 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 impact of climate change on the vegetation state and phenological parameters, including the beginning, end, and duration of the vegetation season, was determined by the normalized difference vegetation index (NDVI), obtained using the data of the infrared (0.72–1.1 µm) and red (0.58–0.68 µm) ranges of the AVHRR radiometer on the website of STAR NESDIS NOAA – Satellite Applications and Research of NOAA's National Environmental Satellite Data Information Services of the USA – http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/. Crop yields and the dynamics of sown areas were determined by the data from the State Statistics Service of Ukraine. The information about the dynamics of the forest cover was obtained using the Global Forest Watch satellite data (https://www.globalforestwatch.org/map/country/UKR). To evaluate the impact of climate change on Ukraine's forests, the investigation was conducted on burnt forest areas, using the MCD64A1 6.1 index, developed on the basis of the MODIS satellite data (https://doi.org/10.5067/MODIS/MCD64A1.061). The additional identification of the burnt areas in the forest cover involved the use of the data from Hansen Global Forest Change v.1.11 (https://doi.org/10.1126/science.1244693). The results of the analysis yielded detailed information about the areas of burnt forests in different regions of Ukraine over an extended period. **Results.** According to the satellite data, the radiation temperature of the terrestrial surface (hereinafter – temperature) during the growing period increased by 2.2 °C on average in the territory of Ukrainian Polissia over the last 40 years. There is a regional difference in the temperature regime observed in the direction from west to east. In the territory of western Polissia, the increase in the temperature of the terrestrial surface in recent decades was within the range of 1.2–1.6, and in the central and eastern parts – within 2.3–2.9 °C. Due to the warming, the duration of the growing period was extended by 21–35 days, mostly because of earlier spring onset. There is a descending trend in the average annual precipitation amount down to 20–30 mm, which is especially notable for central and eastern Polissia. The warming was the reason for the introduction of the crops, new for this region, into the structure of sown areas, especially corn and sunflower, which had a generally positive effect on the vegetation state by the NDVI index, which increased from 0.30 in 1982–1992 to 0.36 in 2012–2022 on average. The crop yield increased accordingly, and according to the statistical data for the recent years, amounted to: corn – 7.0–9.5 t/ha, winter wheat – 4.5–5.0, and sunflower – 1.5–2.0 t/ha, which is close to the level of their yield on chornozem. At the same time, due to climate change and the transformation of agricultural activity, there has been a higher risk of deterioration in the ecological state of typical Polissia landscapes, droughts, and soil degradation. According to the results of the analysis of twenty-two years of the dynamics in forest fires, the largest areas of burnt forests were registered in 2012 (694.30 sq.km), 2015 (1,078.81 sq.km), and 2020 (776.27 sq.km), which demonstrated the increase in fires during the recent decade along with the tendency towards longer fire hazard period. Prior to 2010, the largest areas of the burnt forests were registered in March, April, August, and September, and after 2010, the peaks were also seen in October. At the same time, there was a tendency towards the extension of the wetland areas, especially in the period of 2015–2017. However, their total area in the territory of Ukrainian Polissia is rather variable: there is both a gain and a loss in its area, which is especially notable for central Polissia. In this region, the increase in the area of wetlands has been 18.7 thousand ha in the recent 20 years, with the simultaneous vanishing of up to 14.6 thousand ha. Under the deterioration of hydrological conditions, the expansion of their area may have been associated with the impairment of the land reclamation network infrastructure, which led to the secondary swamping of the reclaimed territories. **Conclusions.** The increase in the temperature of the terrestrial surface of the Ukrainian Polissia during the growing period and the lengthening of the growing period created the conditions for corn and sunflower to be introduced into the arable areas, which had a positive impact on the vegetation state index, NDVI. As a result of these transformations both in the sown area of these crops and their yield, Polissia is becoming a new grain-oil belt of Ukraine. Concurrently, there are higher risks associated with maintaining high performance of agroecosystems and the increase in the risks for soil degradation processes, the deterioration of the ecological state of wetlands and forests, as well as drying-out of small rivers and lakes. Balancing the high yield of modern agroecosystems and safe nature management requires systemic measures in adapting the agricultural activity and nature management to new climatic conditions, which requires implementing the management of soil, water, and bio-resources, achieving optimal parameters of fertility for mineral and peaty-swampy soils. Reconstructing current land reclamation systems to optimize water regimes for the agricultural lands and protect typical Polissia ecosystem is needed.

Key words: satellite data, terrestrial surface temperature, yield, wetlands, growing period, ecosystem, moisture, soil cover, erosion, land reclamation, NDVI.

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INTRODUCTION

Global and regional climate change significantly impacts agricultural production and, consequently, global food safety. Ukraine's agricultural sector is a significant global food producer, and its productivity is also affected by climate change. In particular, the warming of its territory is characterized by the highest rates in Europe – more than 0.7 ºC over ten years (Wilson et al, 2021; Romashchenko, 2024; Balabuh et al, 2021; Balabuh, 2023; Krakovska et al, 2023). However, the degree of impact of such warming on agroecosystem productivity depends on regional natural and climatic conditions. The peculiarities of Ukraine's physical and geographical location determine the allocation of three main natural and climatic zones with the following leading climatic indicators (Adamenko, 2014, 2019):

1. Polissia (mixed forest zone) is a moderately warm zone with an annual precipitation of 600–760 mm and a probability of droughts up to 10 %. The soil cover is characterized by a predominance of acidic turf-podzolic soils of light particle size distribution and organogenic soils within river floodplains and wetlands.
2. Forest-Steppe is a warm zone with unstable moisture provision, a smaller amount of annual precipitation of 575–760 mm, and a probability of droughts of 15–45 %. This area mainly consists of typical chornozem and gray forest soils.
3. Steppe is a very warm zone with even a smaller annual precipitation of 350–540 mm and a probability of droughts of 40–70 %. The soil mainly consists of southern chornozem and chestnut soils.

Intense agricultural activity is conducted in the territory of all three natural climatic zones. Climate change has had a different impact on the productivity of zonal agroecosystems. While in the Forest-Steppe and especially the Steppe zones, higher temperatures have increased the risk of droughts, in the humid zone of Polissia, with its normally sufficient moisture supply, conditions have been created to support previously atypical crops for this zone such as corn, sunflower, soybeans and rapeseed in arable land. At the same time, the area under traditional fodder, spring and winter spiked crops, and especially perennial grasses, has decreased. Such radical changes in the structure of arable areas in Ukrainian Polissia have affected not only agricultural productivity and efficiency but also the state of the soil cover, wetlands, and forests typical for this zone. Therefore, an urgent task today is to establish temporal and spatial patterns of the impact of climate change, in particular, warming, on the transformation of agricultural production and the ecosystem of Ukrainian Polissia, which will become the basis for developing measures to form environmentally safe agricultural production and nature management (Tarariko et al, 2016).

On the European continent as a whole, the physical and geographical area of Polissia is a transboundary region located in 4 countries: Ukraine, Belarus, Poland, and the russian federation. Ukrainian Polissia is a physical and geographical province of mixed forests of the Eastern European Plain, which is characterized by a sufficient level of moisture supply and geomorphologically has the form of a depression with raised edges in the basins of the middle reaches of the Dnipro, Prypiat, and Desna rivers (Polupan and Velychko, 2014).

A general pattern for all three physical and geographical regions of Ukrainian Polissia is the concentration of agricultural land mainly in the southern part of the region. At the same time, in the north, coniferous, broad-leaved, mixed forests and wetlands occupy more than 50–70 % of the territory (**Fig. 1**). The agricultural fields in these territories are predominantly located mosaically on reclaimed lands.

In general, this territory is a kind of a basin, the water reserves of which are probably largely related to the accumulation of meltwater from the last glaciation. As early as the first millennium AD, the territory of Ukraine's humid zone was predominantly filled with oak and pine forests. However, in the eighth century, forest cover dropped to 40 % due to human activity, and by the beginning of the 20th century, it was down to 20 %. The modern landscapes of this area are characterized by their diversity, mosaicism, and fine contours, with pine and mixed forests alternating with river floodplains, lakes, wetlands, and agricultural lands. According to the Johanson-Ringleb index, this zone is characterized by a temperate continental climate with a continentality index of 55–65 (Karamushko et al, 2023). According to the Selyaninov integral hydrothermal coefficient (HTC), it has the following parameters: HTC – 1.3–2.0, annual precipitation – 600–700 mm with a downward trend from west to east (Adamenko, 2014, 2019).

The soil cover of the zone was formed on water-glacial, morainic, loess, and alluvial rocks and is represented mainly by turf-podzolic soils of varying degrees of gley content, sandy and sandy-loamy granulometric composition with low organic carbon content, biogenic elements, high acidity, and a tendency for spraying and deflation (endogenic albeluvisols and umbric gleysols) (Plisko et al, 2021). Considerable areas are covered by meadow-boggy and swampy mineral carbonate soils (humic gleysols, siltic umbric haplic gleysols), and organogenic soils within the river floodplains and wetlands.

Until the 2000s, the Polissia region was characterized as an excessively wet area. To improve the conditions for agricultural activities, in 1965–1990, large-scale works were carried out to drain waterlogged lands in an area of about 3.2 million ha and start arable cultivation. As a result, the structure of landscapes changed significantly; in particular, their ploughed area increased to currently reach 65–85 %. Almost all peat soils, including those within river floodplains, were drained and converted to arable land (Savchuk et al, 2018; Ryzhuk et al, 2022). Up to 80–95 % of the total area of swamps and river floodplains was drained and added to arable lands. As a result, the percentage of arable land on peat soils reached 90 %. Almost all peat-boggy soils were brought into agricultural use, which had a significant negative impact on the swamp flora and fauna and led to the extinction of many plant and animal species. Only about 400,000 ha of peat-boggy lands have been preserved in their natural state, mainly within the state forest fund and nature preservation areas, including the Shatsk and Prypiat-Stokhid national parks (Yatsyk et al, 2019).

However, at present, a significant part of reclaimed peat soils and peat bogs is degraded due to deterioration, subsidence, and secondary waterlogging and is not used in agricultural production (Truskavetskyi, 2010). The land reform and land privatization process resulted in the transfer of a rather developed on-farm land

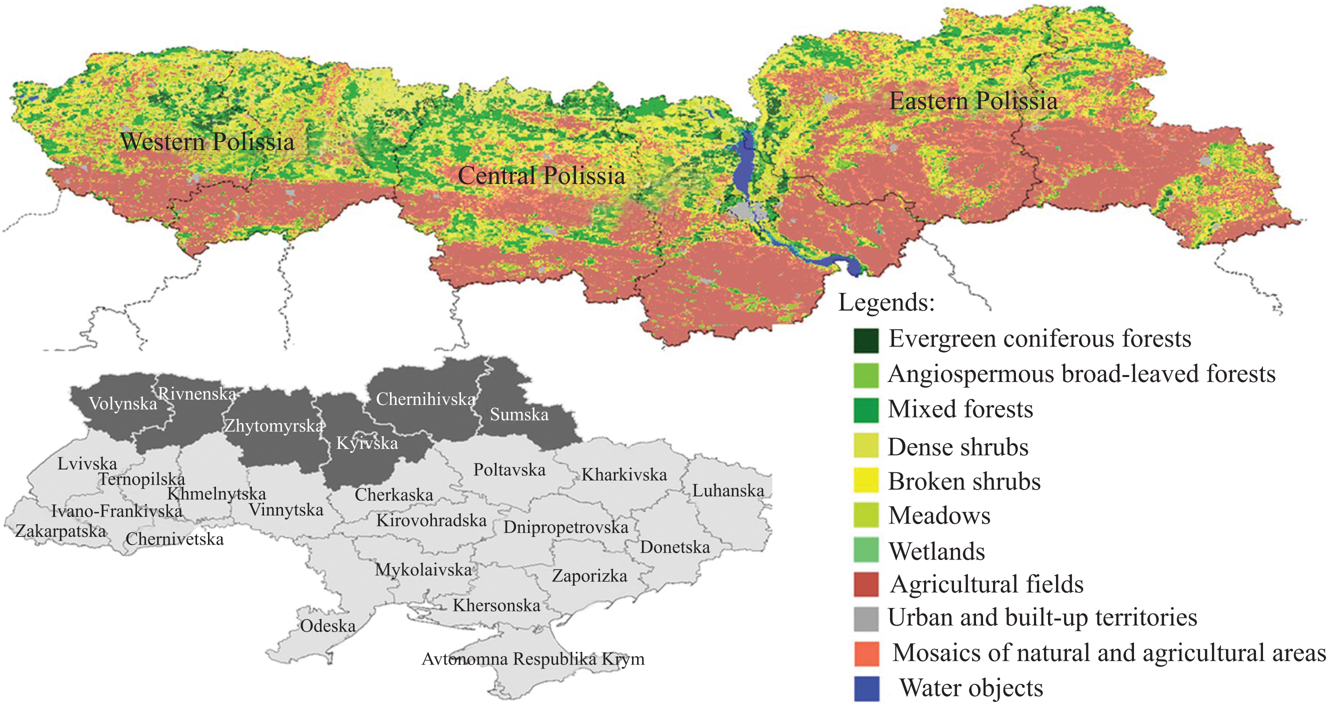

Fig. 1. The map of the terrestrial surface classes in the investigated territory, the informational product of Copernicus Global LandCover 2019 (https://land.copernicus.eu/en/products/global-dynamic-land-cover/copernicus-global-land-service-land-cover-100m-collection-3-epoch-2019-globe)

reclamation network to communal ownership, which negatively affected its technical condition, especially the land reclamation systems with a two-way water regime. As a result, the effective use of reclaimed land has significantly decreased and is currently carried out on an area of about 1,700 thousand ha. When the infrastructure of reclaimed lands is impaired under excessive precipitation in some years, the groundwater level may return to its original state, leading to their secondary waterlogging and swamping, and when there is a shortage of rain, the processes of overdrying and moisture deficit are observed (Romashchenko, 2024). Even with spring moisture reserves in the one-meter soil layer of 120–170 mm, in summer, they can drop to critical 60–80 mm, and the groundwater level – to 2.0–2.5 m with a drainage depth of 1.1 m (Romashchenko and Tarariko, 2017; Ryzhuk et al, 2021).

Due to climate warming, in the territories with drained organogenic soils, there is a decrease in their waterlogging, and in years with little moisture content – even drying out. Yet, in general, under optimal management of water and air soil regime, climate warming has had a positive impact on the performance of agroecosystems. Under additional heat resources even in conditions of natural hydration of the drained turf-podzolic soil, one can achieve corn grain yield at the level of 7.6–10.4, soybeans – 2.3–2.7, and sunflower – 2.3–2.9 t/ha, and in case of regulating the water, air, and nutrient regime, yields may increase by 16.7–25 % (Ryzhuk et al, 2022). On reclaimed river floodplains on organogenic soils in crop rotations with 5–6 fields of perennial grasses, 2–3 fields of corn and sunflower, yields reach 8.4–8.7 and 2.6–2.7 t/ha, respectively (Sliusar et al, 2023).

Due to warming and a tendency for lower precipitation in western Polissia with drained organogenic soils, there is a decrease in waterlogging, which also creates favorable conditions to cultivate corn and sunflower with a similar yield level. As a result, crop production throughout Polissia has become quite competitive, particularly in comparison with the Forest-Steppe zone with typical chornozem and grey forest soils. Perennial research by the Institute of Agriculture of Polissia of the National Academy of Agrarian Sciences of Ukraine has shown that maintaining high productivity of modern agroecosystems, sustainability over the years, requires improving the management of the water and air regime of the soil and achieving optimal soil fertility parameters (Faybishenko et al, 2023).

The current farming intensity of agricultural landscapes in Ukrainian Polissia, the unsatisfactory state of the land reclamation network, the increase in the field area, intensive tillage in modern crop rotations, the decline in groundwater levels, periodic overdrying of peatlands, and the reduction in the area under perennial grasses and fodder crops have led to large-scale degradation processes of deflation, water erosion, dehumification of turf-podzolic soils, and destruction of organogenic soils. Under long-term use, modern draining land reclamations worsen such physical and chemical parameters of the soil as the amount of absorbed alkali, absorption capacity, organic carbon content, and leaching of silt fractions from the upper soil layers (Hordiychuk and Stakhiv, 2011).

Modern socio-economic transformations and land privatization have led to a disruption of the functioning of the integral land reclamation network. As a result, part of the reclaimed land is now undergoing secondary waterlogging or overdrying. The best solution in this situation is to re-naturalize such lands, i.e., return them to their original state, which is especially important from an environmental point of view for river floodplains and wetlands with peat-bog soils (Truskavetskyi, 2010). As a result of climate change, agricultural activities in Ukrainian Polissia are changing quite dynamically, and degradation processes in ecosystems are observed. In this regard, it is important to establish the patterns of positive and negative aspects of climate change impact on agricultural activities and nature management to form ecologically balanced agroecosystems of different specializations and nature-conserving management.

Forests are the most critical element of the ecosystems and landscapes of Polissia. Rising temperatures, abnormally high summer temperatures, draining waterlogged and wetlands in the middle of pine forests have created conditions for an increased fire hazards in forests and damage to pine habitats by pests and diseases, in particular, the pine bark beetle and other xylophages. It should be noted that such negative processes are global in nature and are observed not only in Ukrainian Polissia but also in pine forests of the USA, Canada, Belarus, and other countries (Karamushka, Boychenko, Nazarova, 2022; Hetmanchuk, 2017, Zeng et al, 2021).

Thus, climate change and large-scale land drainage in Ukrainian Polissia have created conditions for the most dynamic transformation of both agricultural production and ecosystems compared to other natural and climatic zones. In this regard, it is crucial to establish the temporal and spatial patterns of climate change impact on the state of vegetation, the structure of sown areas, crop yields, and ecosystem elements to develop measures to adapt to the warming, taking into account the regional characteristics of Ukrainian Polissia.

MATERIALS AND METHODS

The research was conducted in six administrative regions within Ukrainian Polissia. The selected areas were grouped into three territorial objects (regions) of investigation by similar natural climatic conditions and the area of the land reclamation drainage (Fig. 1):

1. Western Polissia (Volyn, Rivne regions) – up to 50–60 % reclaimed lands;
2. Central Polissia (Zhytomyr and Kyiv regions) – up to 20–25 % reclaimed lands;
3. Eastern Polissia (Chernihiv and Sumy regions) – up to 10–15 % reclaimed lands.

The impact of climate change on agricultural production and the ecosystem elements was determined by the satellite and statistical data from the State Statistics Service of Ukraine. The data from satellites Sentinel-2, Moderate-Resolution Imaging Spectroradiometer (MODIS), Visible Infrared Imager Radiometer Suite (VIIRS), or Proba-V were used since they provide NDVI times series with rather high spatial resolution. Yet, the only sensor providing long-term time series for four decades, the Advanced Very High-Resolution Radiometer (AVHRR), allows for the creation of time series of NDVI, reaching the early 1980s on the global, national, and regional scales (Kogan, 2001). The use of satellite and statistical data on the yield of major crops covering a long period of time made it possible to identify climatic and statistically significant changes in temperature regime, moisture supply, state of the vegetation during the growing season, agroecosystem productivity, and the occurrence of degradation processes.

The phenological land surface parameters (LSP), which consist of determining the beginning and end of the growing season, were determined using the satellite data for determining the phenological land surface parameters (LSP) – the start of the growing season (SOS) and the end of the season (EOS), which made it possible to determine how vegetation responds to long-term climate fluctuations. Contrary to ground-based observations of individual phenological phases of plants, satellite LSPs provide only more general estimates of phenological changes (Kukal and Irmak, 2018). For instance, the determination of the SOS allows for additional assessment of the productivity of vegetation cover (Stendardi et al, 2019). At the start of the growing season, the process of photosynthesis begins, which is accompanied by a higher accumulation of plant biomass and an increase in the spectral characteristics of the vegetation cover (Zang et al, 2003). The approaches, used to determine LSP, and the time series of vegetation indices, such as NDVI, are usually based on: 1) reaching the fixed value (i.e., the SOS date when NDVI exceeds a certain value, e.g., NDVI > 0.2); 2) using the dynamic threshold (e.g. 50 % of the annual maximum, calculated for each pixel) (Fisher et al, 2007); 3) evaluating the rise velocity (i.e. the date when the NDVI curve starts rising sharply or when the first derivative is the highest) (Zhang et al, 2003).

The normalized difference vegetation index was used in the research (Kogan, 2001), which is a combination of spectral characteristics of the vegetation cover, defined as

$$\text{NDVI} = (\text{NIR} - \text{RED})/(\text{NIR} + \text{RED}),$$

where NIR and RED are the values for spectral brightness in the close infrared spectrum range (0.70–1.0 μm) and the visible (red) spectrum range (0.58–0.68 μm). The NDVI values fluctuate from –1 to +1.

To determine the seasonal phenological dynamics of the vegetation and its changes in perennial perspective, we used the weekly NDVI index data for forty years (1982–2022) based on the available information of satellite systems of low spatial resolution from the database of the NOAA STAR NESDIS (Center for Satellite Ap-plications and Research of NOAA's National Environmental Satellite Data Information Services http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH). The corresponding monitoring was conducted using the multizonal high-precision radiometers AVHRR and VIIRS on artificial meteorological satellites of the Earth NOAA-7, NOAA-9, NOAA-11, NOAA-14, NOAA-16, NOAA-18 and NOAA-19, which ensure multispectral shots of practically the entire surface of the Earth twice a day in the ranges of 0.58–0.68; 0.725–1.1 μm; 3.55–3.93; 10.3–11.3; 11.4–12.4 μm. The spatial resolution of this NDVI data set was 1.1 km, and the swath width – about 3,000 km. Due to severe gaps in the data for 1994, 1995, and 2004, they were excluded from the analysis. The comparative analysis of perennial trends and seasonal cycles of the NDVI index was conducted.

The charts for 40 years (1982–2022) were built to reflect the annual dynamics in the changes of the terrestrial surface temperature during the growing period in the investigated regions by the SMT (Smoothed Temperature) index – the weekly temperature of the Earth's surface, averaged by regions and calculated as the radiation temperature of the surface using the data of the infrared range (10.3–11.3; 11.4–12.4 μm) according to the LSA SAF method (García-Haro et al, 2021).

The precipitation dynamics from 1979 till 2022 was determined 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 within each administrative regios was determined by the data of the State Statistics Service of Ukraine in 1990–2022, and its association with NDVI – by the correlation regression analysis.

The analysis of the impact of climate change on forest ecosystems involved the study of the long-term data about the burnt forest areas in different regions of Ukraine, based on the use of the burned area index MCD64A1 6.1, developed on the basis of the MODIS satellite data (a link: https://doi.org/10.5067/MODIS/MCD64A1.061). This index is a monthly global product with a swath stripe of 500 m, which combines the data of the reflective power of the surface, obtained from the Terra and Aqua satellites, with the active surveillance of fires in the territory of 1 sq.km for accurate mapping of the burnt territories. Additionally, to identify the burnt areas within the forest cover, we used the data set about the forest cover from Hansen Global Forest Change v1.11 (Hansen et al, 2013) for 2022. This analysis yielded detailed information about the areas of burnt forests in different regions of Ukraine over an extended period.

RESULTS OF INVESTIGATIONS

Temperature. The temperature of the growing period is one of the defining factors of positive or negative impact on agricultural vegetation and ecosystems. Using the satellite data, it was determined that over the recent 40 years, a natural increase in the temperature of the Earth's surface during the growing season had been observed in the Ukrainian Polissia zone. While in the first decade of the observation period (1982–1992), the average temperature of the growing season within the zone was 15.5 ^{o}C, in the fourth decade (2012–2022) it reached 17.7 ^{o}C. There is a regional difference in the increase in the temperature of the Earth's surface during the growing season. In western Polissia, it increased by 1.2–1.7 °C, in central Polissia – by 2.5–2.9 °C, and in eastern Polissia – by 2.2–2.5 °C over these periods. Thus, the highest rates of temperature increase during the growing season are observed in central and eastern Polissia. At the same time, from 1992 to 2001, cooling was observed in western Polissia with a decrease in the mean temperature during the growing season by 0.2–0.3 °C, while in central and eastern Polissia, the temperature increases continued (**Table 1**).

A reduction in annual precipitation, coupled with an increase in temperature during the growing season, may have adverse effects on agricultural production.

Two time periods can be distinguished during these 40 years: the first period, covering 1982–2006, when the temperature increased more slowly, and the second period (2008–2022) with more rapid warming (**Fig. 2**). It is evident that during the second period, the number of years with a cooler growing period, i.e., the years when the summer climate became more even in terms of years, decreased in all the Polissia regions.

But in general, the increase in the temperature of the Earth's surface during the growing season in Polissia has been going on for 40 years, with some acceleration in recent decades. Thus, if this pattern and rate of the warming continue, their impact on agricultural production is likely to increase, and the risks of drought events, water resources shortages, and the need to develop measures of adapting to new climate conditions will increase.

Providing moisture to vegetation during the warming of the growing season is critical for both agricultural production and the functioning of ecosystems. Precipitation per year is decreasing from west to east. In western Polissia, the precipitation amount is 755 mm, in central Polissia – 702 mm, and in eastern Polis-

Table 1. The dynamics in the growing period temperature over 40 years (1982–2022) in ten-year-long cycles, °C

Polissia	Years			
	1982–1991	1992–2001	2002–2011	2012–2022
Western				
Volyn	15.7	15.4	17.2	16.9
Rivne	15.5	15.9	17.4	17.2
Central				
Zhytomyr	15.4	15.4	17.5	17.9
Kyiv	16.3	16.4	18.5	19.2
Eastern				
Chernihiv	15.5	15.9	17.7	18.0
Sumy	14.5	15.0	15.9	17.0
On average	15.5	15.7	17.4	17.7

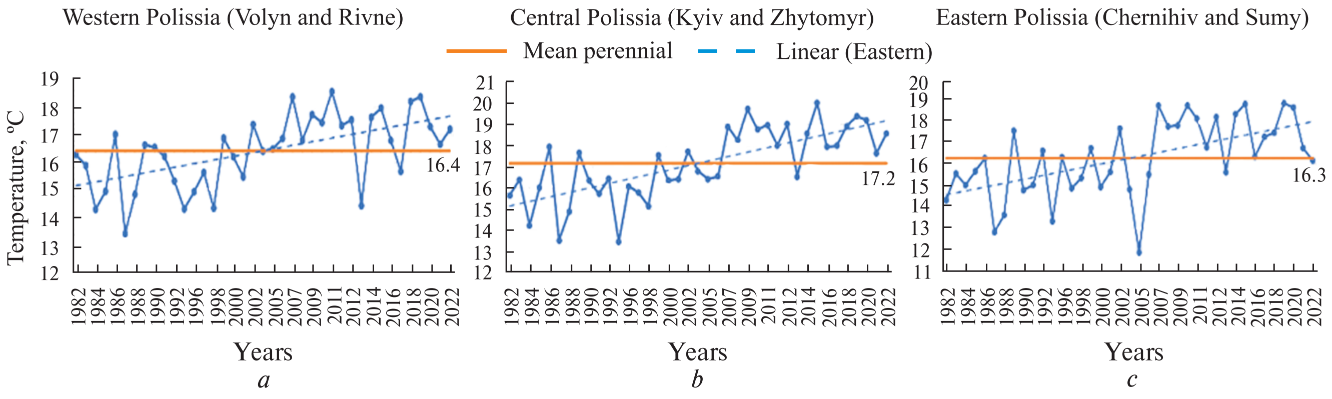

Fig. 2. The dynamics of the mean temperature of the Earth's surface for the growing period in western (*a*), central (*b*), and eastern Polissia (*c*)

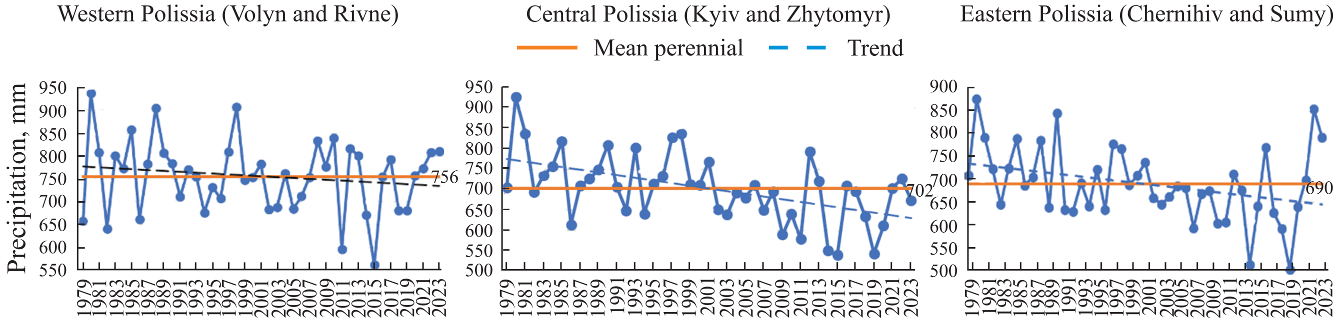
Western Polissia (Volyn and Rivne)
Central Polissia (Kyiv and Zhytomyr)
Eastern Polissia (Chernihiv and Sumy)

Fig. 3. The dynamics of the annual precipitation amount for the 44-year-long period by regions in the Polissia zone, mm (built by the authors using the ERA5 data of ECMWF/Copernicus Climate Change Service (https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#description)

sia – 690 mm per year. Annual precipitation trends for 1978–2023, i.e., for 44 years, are downward in all Polissia regions (**Fig. 3**).

The rate of annual precipitation decline has especially accelerated in the past 20 years. The deviation from the long-term average from 1979 to 2023 is from 30–40 mm in eastern and central Polissia, with the lowest deviation in western Polissia – about 20 mm. In the last 10–15 years, the number of dry years has been increasing, which is especially typical for western and eastern Polissia (**Fig. 4**). As seen in Fig. 3, the number of dry years has also been increasing in the last decade, which will have a negative impact on both crop yields and the condition of such ecosystem elements as surface water, wetlands, meadows, and forests.

If we compare precipitation amount over the past 40 years and the average temperature during the growing season, we can clearly see their opposite trends, which indicates an increase drought risk. Thus, in the context of climate warming, and increased evaporative demand and reduced precipitation, the most important factor in ensuring high productivity of agroecosystems is better management of available water resources in landscapes through its accumulation and subsequent use during the growing season under dry conditions. Additionally, renaturalization of degraded reclaimed lands of swamps and river floodplains is critical.

The state of vegetation based on NDVI. Rather dynamic changes in the heat and water regime of the growing period undoubtedly have a considerable effect on the vegetation state. A common satellite meth-

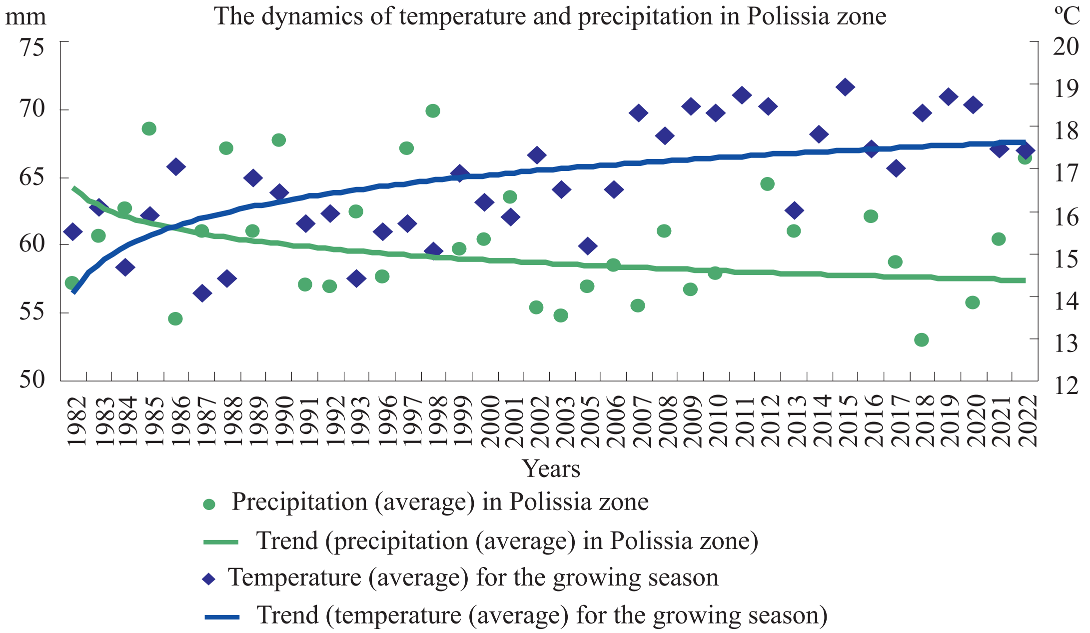

Fig. 4. The dynamics of the annual precipitation amount and the mean temperature of the Earth's surface for the growing period 1982–2022 Ukrainian Polissia

od of determining the vegetation state is the NDVI index. When it was used to assess the impact of the growing season warming on the state of vegetation, including crops, it was assumed that the area of natural lands remains relatively stable over the years, while the NDVI of agricultural lands was dynamic and depended on the level of agricultural technology, the structure of sown areas and, in particular, the increase in the area under crops with an extended growing season. Therefore, NDVI is an important indicator for assessing the impact of climate change on the general state of vegetation and on the sown crop fields in particular. Table 2 presents the NDVI dynamics in ten-year-long cycles over 40 years. Its mean value for the vegetation period increased from 0.30 in the first decade (1982–1991) to 0.36, or by 20 %, in the fourth decade (2012–2022) (**Table 2**). There seems to be a positive relationship between the temperature increase over 40 years and the improvement in the vegetation state based on the NDVI index, which is especially notable for western Polissia **(Fig. 5**). The comparison of 20-year-long cycles for this indicator demonstrates this pattern even more vividly. In the second half of the 40-year-long period, as compared to the first one, the NDVI index increased by 37 %, which coincided with a higher tempo of the temperature rise during the growing period (Table 2).

Climate warming during the period from 2003 to 2022 had a positive impact on the vegetation state, according to NDVI, in the territory of western Polissia compared to central and eastern Polissia (Fig. 5).

In general, over the 40-year period, the pattern in the Polissia zone is that of rising temperature during the growing season accompanied by a corresponding improvement in the state of vegetation, which also ap-

Table 2. The dynamics in the NDVI for the growing period over 40 years (1982–2022) in ten-year-long cycles for the regions of the Ukrainian Polissia zone

Polissia	Years			
	1982–1991	1992–2001	2002–2011	2012–2022
Western				
Volyn	0.31	0.33	0.37	0.37
Rivne	0.30	0.32	0.36	0.36
Central				
Zhytomyr	0.31	0.34	0.36	0.37
Kyiv	0.30	0.32	0.33	0.34
Eastern				
Chernihiv	0.31	0.34	0.35	0.36
Sumy	0.29	0.32	0.34	0.35
On average	0.30	0.33	0.35	0.36

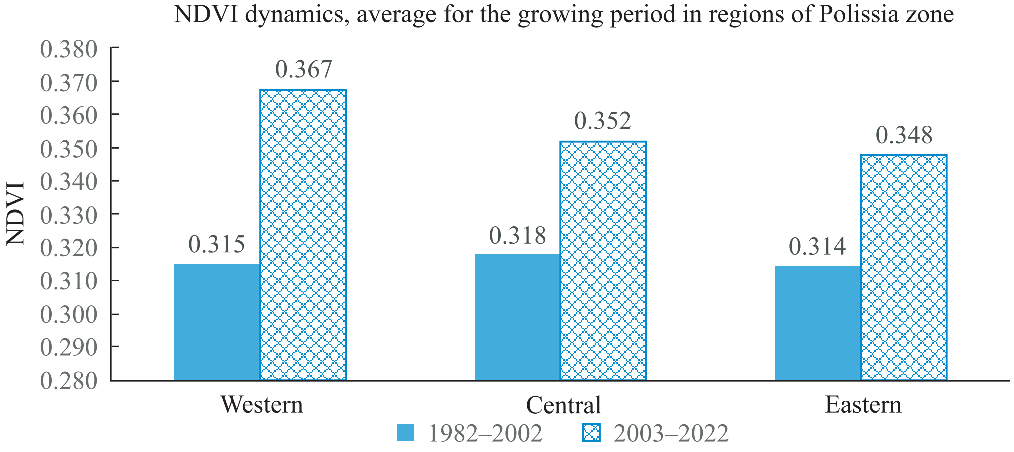

Fig. 5. The dynamics in the NDVI for the growing period in the regions of the Ukrainian Polissia zone

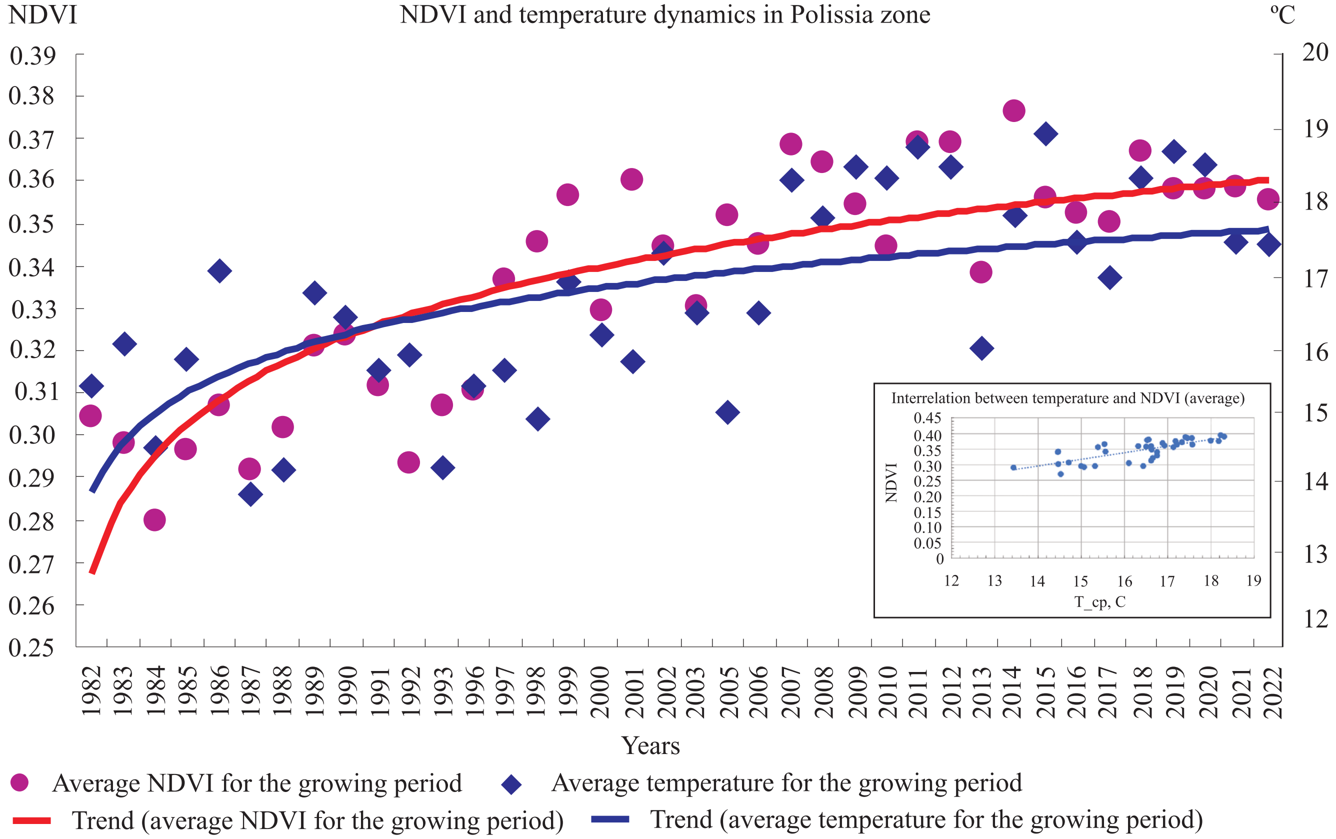

Fig. 6. The interrelation between warming during the growing period and the vegetation state based on the NDVI in the Ukrainian Polissia

plies to the crop fields (**Fig. 6**). There is a reasonably close correlation between the increase in the Earth's surface temperature and the state of vegetation according to the NDVI in all three regions of Polissia (Fig. 6). The highest value of the correlation coefficient is observed in western and central Polissia – within the range of 0.73–0.74 and slightly lower in eastern Polissia – 0.52, which is explained by the more extensive forest cover and smaller area of agricultural land, as the increase in NDVI is higher within agrarian land due to the extended growing season and higher biomass of agroecosystems.

Obviously, the positive impact of the warming on the vegetation state is associated with the duration of the growing season and improved conditions for biomass accumulation and leaf surface formation, which is especially true for crop fields. Therefore, it is essential to determine the impact of the warming on the start and end of the vegetation cycle along with onset of different phenological stages. These dates are the start of the photosynthetic activity or the growing season (SOS), the middle with the maximum leaf surface area and the end of the growing season with the cessation of photosynthetic activity, with the area of green leaves decreasing to the state characterizing the end of the growing season (EOS). Using this pattern and comparing it over time makes it possible to determine the impact of warming on the length of the growing season (Zhang et al, 2003). The key time points of the start (SOS) and end (EOS) of the vegetation period were determined by the moment when the values of the vegetation index, NDVI, exceeded some threshold values (Siłuch et al, 2022). The soil and climatic conditions of Ukrainian Polissia are characterized by the initial growing season, NDVI values usually less than 0.2, which characterizes the terrestrial surface without vegetation or the start of seedling formation. At the beginning of the growing season, there is a gradual increase to 0.3–0.8, and at the end of the growing season, it decreases again to 0.2. Therefore, the dates of the SOS and EOS were accepted as the time when the NDVI curve crosses the value of 0.2. In this regard, the comparison of two-decade cycles of the 40-year period was the most informative: the first (1982–1992) and the fourth one (2012–2022). The last ten-year cycle of the growing season in Polissia starts 14 days earlier and ends seven days later, as shown in **Fig. 7**. However, there are some regional differences between western, central, and eastern Ukrainian Polissia (**Table 3**).

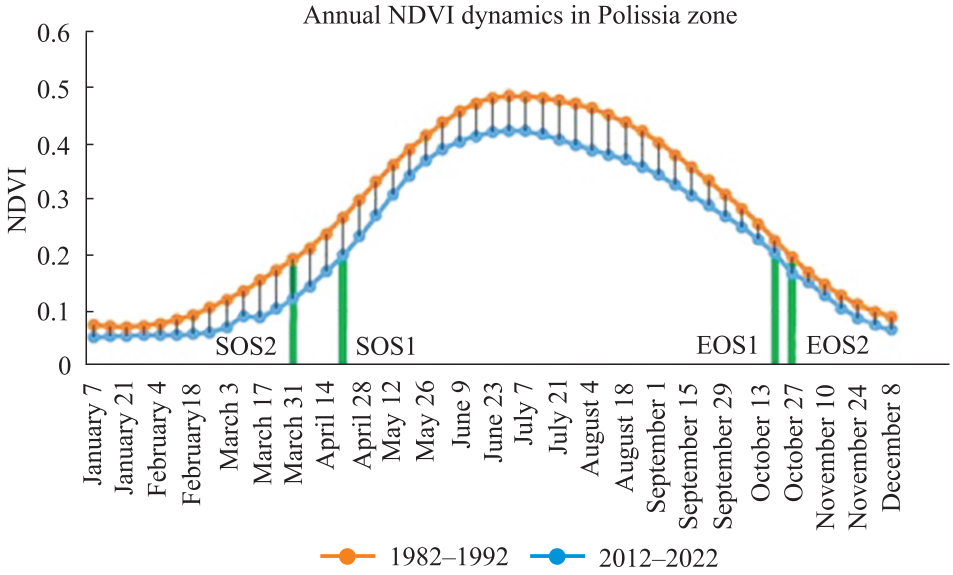

Fig. 7. The comparative dynamics of NDVI during the growing period on average in the Polissia zone in the first and fourth decades

The greatest increase in growing season length was observed in western Polissia – 35 days, while in central and eastern Polissia, it extended for 21 more days. This extension of the vegetation period has undoubtedly created opportunities for the introduction of new crops with a longer vegetation period which had a general positive impact on the NDVI index.

The positive impact of the warming on the vegetation state during the growing period is also related to the increase in the performance of crops. As shown above (Fig. 6), there is a correlation between the increase in the Earth's surface temperature during the growing period and the vegetation state. However, there is also a rather close correlation between the state of vegetation based on the NDVI and the yield of crops, including corn in eastern Polissia (**Fig. 8**).

This correlation is also observed for corn in western and central Polissia, but it is weaker. This relatively close correlation between the vegetation state index and the yield of crops is an effective instrument for evaluating the state of the sown areas even in Polissia. The yield of corn, sunflower, and winter wheat is presented

Table 3. The regional differences in the growing period duration according to the comparison of the first and the fourth decades of the 40-year-long period

Periods (years)	Start of the growing period, DD.MM	End, DD.MM	Duration, days
Western Polissia			
First decade (1982–1992)	14.04	14.04	
Fourth decade (2012–2022)	31.03	31.03	
Difference, days	21	21	35
Central Polissia			
First decade (1982–1992)	21.04	21.10	
Fourth decade (2012–2022)	7.04	27.10	
Difference, days	14	7	21
Eastern Polissia			
First decade (1982–1992)	28.04	13.10	
Fourth decade (2012–2022)	14.04	20.10	
Difference, days	14	7	21

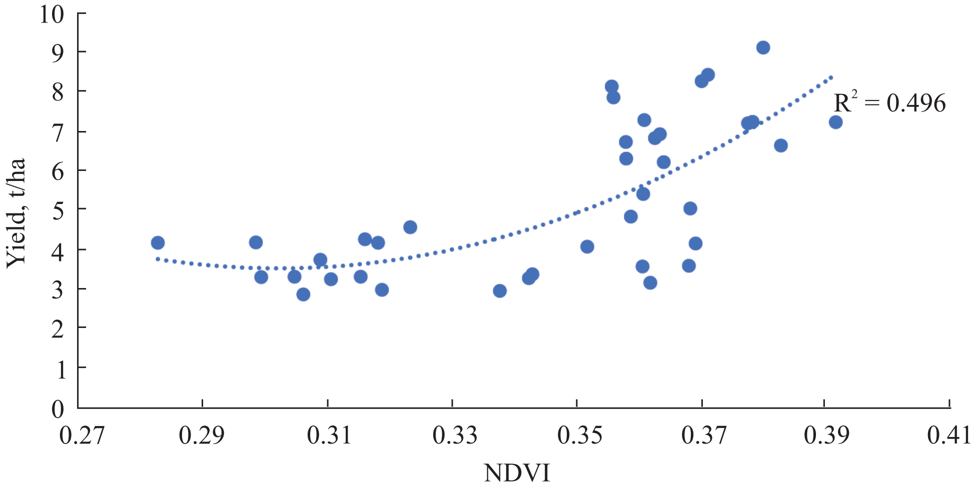

Fig. 8. The correlation between NDVI and the corn yield in eastern Polissia

according to the data from the State Statistics Service of Ukraine. The increase in crop performance over time was generally simultaneous with both the warming and the improvement in the vegetation state. This pattern became particularly noticeable from 2000 to 2006, which coincided with the period of rapid increase in the growing season temperature (Fig. 2) and its positive impact on the vegetation state.

The current system of qualitative assessment of the resource potential of Ukrainian soils associated with the heterogeneity of their typological composition and a wide range of soil formation conditions provides for determining soil productive capacity for the agricultural potential of major crops (Polupan et al, 2005).

We determined soil quality based on the yield data from long-term stationary (30–40 years) field experiments (about 200), absolute controls (agropotential of natural fertility), and backgrounds with optimal fertilizer and ameliorant application (agropotential effective fertility) of the network of the National Academy of Agrarian Sciences of Ukraine (NAAS), the Ministry of Agrarian Policy of Ukraine, universities of the Ministry of Education and Science of Ukraine and research institutes, and other agencies.

The study of crop yield parameters under natural and effective fertility has been carried out since the 1960s when intensive varieties began to prevail in Ukrainian crop production. The first generalization was conducted and published for 40 years (1960–2000) (Polupan et al, 2005; Velychko, 2010) and the second one – in 2015 (Polupan et al, 2015).

Turf-podzolic soils prevail in the soil cover structure of Ukrainian Polissia, covering almost 50 % of the agricultural fields (Breus, 1993). In the Polissia zone, the parameters of winter wheat performance are determined by the ecologic-genetic status of soil, their granulometry and hydromorphosis degree, for instance, the productive ability of the crops increases in case of natural fertility of heavier turf-podzolic soils and decreases in case of gleization (Polupan et al, 2015). In case of effective fertility the yield of crops is similar. In general, turf-podzolic soils are favorable for the cultivation of winter wheat. This is why, at the beginning of the 20th century, H. Makhov called them “wheat soils” (Makhov, 1922).

In the context of the natural and ecological changes in the growing period in 1960–2015, the average annual parameters of winter wheat agropotentials regarding fertility efficiency of turf-podzolic soils of Polissia increased from 3.7 to 4.3 t/ha.

As a traditional and widespread crop in Ukraine, corn is demanding not only favorable soil conditions but also moisture (but not excessive) and heat. The changes in natural and climatic conditions, particularly in the Ukrainian Polissia region, have contributed to extending the growing season duration from 21 to 35 days (Table 2). Accordingly, these changes affected the parameters of corn agropotentials. While the agropotentials of corn for grain under effective fertility over 40 years (1960–2000) averaged 3.8–4.4 t/ha, in 2015, it increased by almost half and reached 3.9–6.3 t/ha, which coincided with increasing in the temperature of the growing season (Fig. 2).

As a result of the warming of the growing season, its longer duration, and improved cultivation technologies, including increased fertilizer doses, the yields in

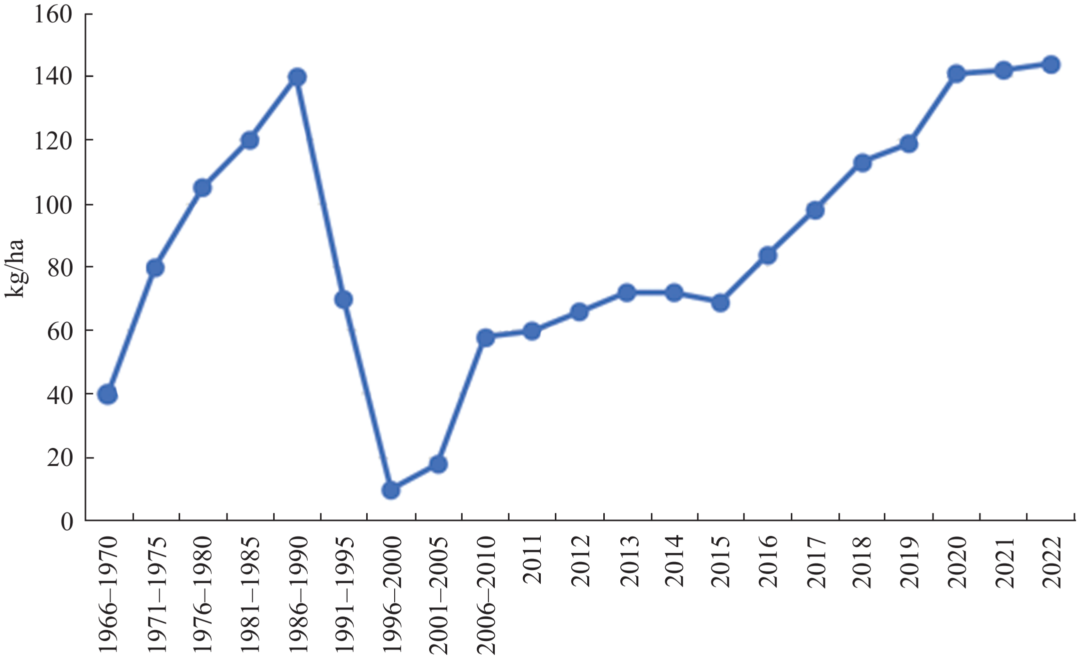

Fig. 9. Fertilizer use in Ukraine's agriculture from 1966–1970 to 2022, kg/ha, active substance (NPK). (source: Baliuk et al, 2015), according to the official data of the State Statistics Service of Ukraine for 2014–2022

the Polissia region (according to the State Statistics Service of Ukraine) are now reaching the following levels: corn – 8–10, sunflower – 2.5–3.0, and winter wheat – 4.5–5.0 t/ha. Obtaining such high crop yields in the Polissia zone on turf-podzolic soils is approaching the level of performance, traditional for growing these crops in the Forest-Steppe zone, where more fertile chornozem and grey forest soils predominate. This is due not only to the warming and longer growing season in this zone, but also to improved agricultural practices, especially the increased use of fertilizers, which has allowed for the efficient use of additional heat resources. In Ukraine, including the Polissia region, over the period from 1966–1970 to 1986–1990, the average annual use of mineral fertilizers increased from 46 to 148 kg of active substance (NPK) per hectare of sown area, which at that time created conditions for the effective use of the existing natural resource potential of reclaimed lands in Polissia (**Fig. 9**) (Baliuk et al, 2015; Baliuk, Khareba, Kucher, 2022). Yet, in the process of modern social and economic transformations, the amount of the introduced mineral fertilizers (NPK) in 1991–1995 decreased to 20–25 kg/ha. As a result, there was a negative balance of nitrogen, phosphorus, and potassium in crop rotations, which had a negative impact on soil fertility and the yield of all the cultivated crops.

From 2006 till 2010, the doses of fertilizers started gradually increasing, and by 2020–2022, they reached almost 140 kg/ha, i.e., almost the level of 1981–1985 (Fig. 9). Yet, at the time, the yield of corn, sunflower, and winter wheat was still lower as compared with the current period, regardless of the same amounts of mineral fertilizers (**Fig. 10**).

Therefore, it can be concluded that the additional increase in crop yields in the Polissia zone over the past decade was due to the impact of the warming and increased growing season length.

One of the phenomena of the positive impact of climate change on the vegetation state and crop performance under a significant increase in temperature, reduced precipitation and additional moisture losses due to evaporation is its more efficient use in the process of transpiration. The warming and extension of the growing season, as well as improved agricultural practices and especially increased fertilizer doses, result in a larger leaf area and, accordingly, a more complete coverage of the open soil surface, which reduces moisture losses through evaporation. As a result, more moisture is available for transpiration, which compensates for decrease in precipitation. Faster rates of leaf development shields the soil surface from solar energy, reducing evaporation from the soil surface and conserving water for transpiration.

Thus, maintaining optimal soil fertility important for efficient use of available water and heat resources to form highly productive agroecosystems as we adapt

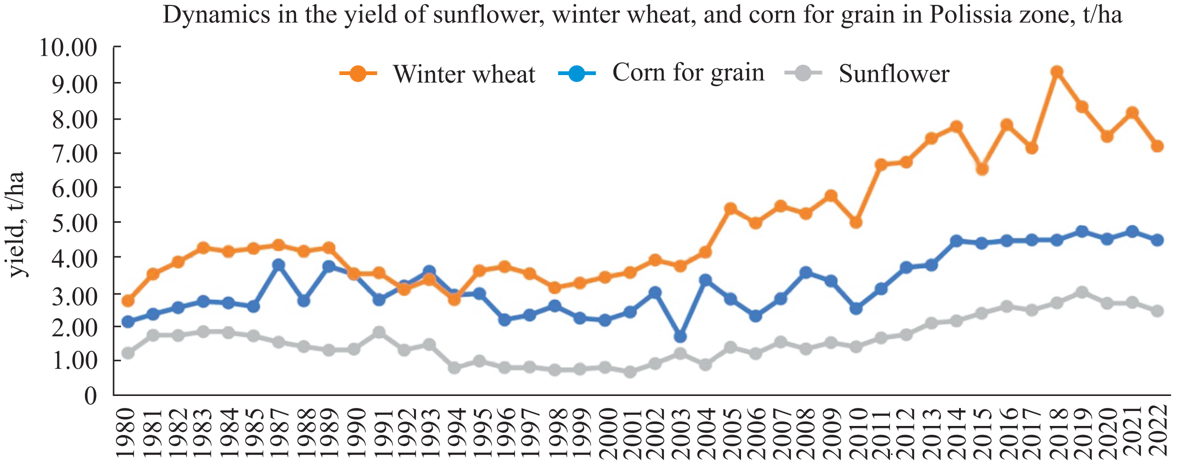

Fig. 10. The dynamics in the yield of winter wheat, corn, and sunflower on average in the Ukrainian Polissia zone. (Built by the authors using the official data of the State Statistics Service of Ukraine)

to climate change. In general, it can be concluded that climate change over a 40-year period in the natural climatic zone of Ukrainian Polissia has had a positive impact on the state of vegetation and the yield of winter wheat and even more of corn and sunflower. However, due to the warming and uncontrolled expansion of sown areas of the crops new to Polissia, the risks of soil degradation have increased in recent years.

One of these risks is higher fire hazards in forest ecosystems. The analysis of the areas, burnt over 20 years, from 2002 to 2022, within Ukrainian Polissia, demonstrated a considerable increase in the area of forests, damaged by forest fires, especially since 2010, and a significant variability of burnt areas in six regions of Ukrainian Polissia (**Fig. 11**).

Some of the largest burnt areas were observed in 2012 (694.30 sq.km), in 2015 (1,078.81 sq.km), and in 2020 (776.27 sq.km), which highlights the increase in fires in the recent decade.

In general, there are some regional specificities. For instance, in the Chernihiv region (eastern Polissia), there was a considerable increase in the burnt area in 2014 (230.15 sq.km) and 2015 (205.77 sq.km), with subsequent peaks in 2019 and 2020. Early 2000s witnessed considerably smaller areas of burnt forests, which demonstrates the deterioration of conditions over time. In the Kyiv region (central Polissia), there were significant peaks in 2011 (96.13 sq.km), 2015 (233.26 sq.km) and 2020 (223.34 sq.km), which demonstrates a gradual increase in fire hazard. In the Zhytomyr region (central Polissia), some of the largest burnt areas were observed in 2002, 2012, 2015, and 2020, with a massive peak in 2020 (392.19 sq.km), which highlights the increase in fires in recent years. In the Rivne region (western Polissia), an especially large burnt area was observed in 2002 (211.62 sq.km), and in 2012 and 2015, with a visible peak in 2020 (93.25 sq.km). At the same time, the Sumy region (eastern Polissia) was characterized by moderate but stable fire activity, with the highest indices in 2005, 2014, and 2019. In the Volyn region (western Polissia), there was generally lower fire activity with a peak in 2012 (132.29 sq.km), which demonstrated a relatively low frequency of massive fires in this region.

There has also been a tendency towards the extension of the fire hazard period in the recent decade. While in 2002–2010, the largest areas of burnt forests were registered in March, April, August, and September, in the period after the 2010s, some peaks of burnt areas were also found in October.

In general, it demonstrates the increase in fire activity and burnt areas with time in different regions of Ukraine, including Chernihiv, Kyiv, Zhytomyr, and Rivne regions, with specific increases in 2012, 2015, and 2020. These changes indicate the deterioration of conditions and the extension of the fire hazard period which now includes October.

DISCUSSION

The climate change signal is significant in the Polissia zone with significant production implications. However, the strength of the climate change signal and production implications observed in the other highly productive agricultural zones may differ from that observed in this study, which has global food production and economic implications. Selected contrasts to Iowa, USA will be noted as this Midwest USA area has soils and climate similar to those in the Polissia zone, but has a consider-

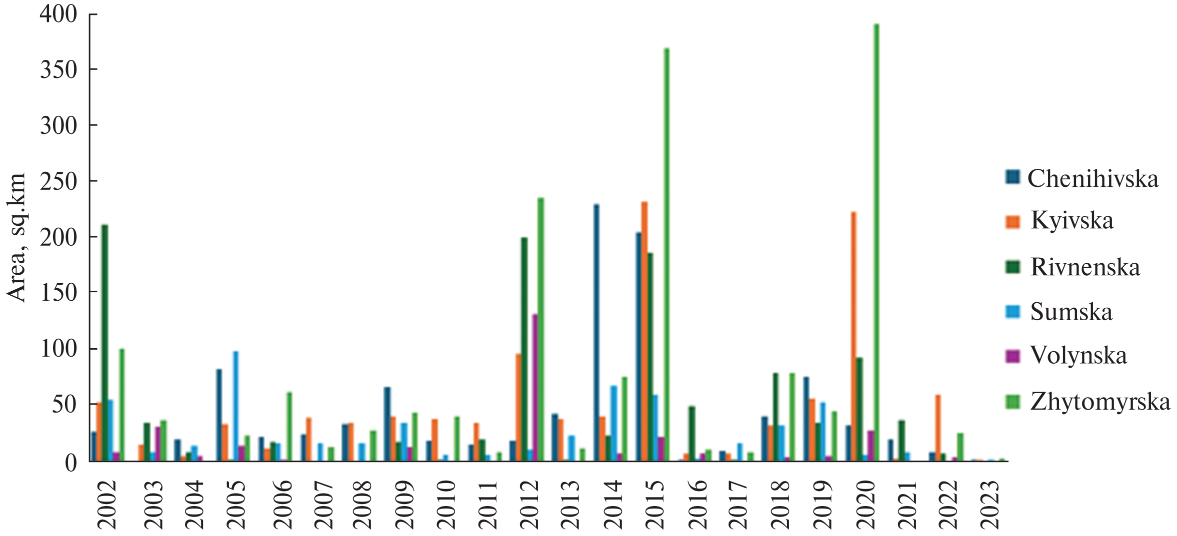

Fig. 11. The dynamics in the area of the burnt forests in six regions of Ukrainian Polissia in 2002–2023

ably fainter climate change signal resulting in different production and natural resource implications.

Grains, grain legumes, and technical crops currently account for the largest share of Ukraine's total acreage, covering 50 and 30 % of the total sown area, respectively. There is a steady upward trend in sunflower and corn fields with time, driven not only by market demand but also by climate warming, which is particularly important for the Ukrainian Polissia zone. Overall, agricultural production in this area responded quickly to the changing climate and the increased growing season length and made good use of the additional heat resource by introducing high-yielding crops such as corn, sunflower, soybeans and rapeseed, which had not been previously grown in significant volumes in the Ukrainian Polissia zone, into the structure of the sown areas. A significant increase in corn and sunflower fields was observed starting from 2008–2010, which coincided with the period of the most intense warming of the growing season. At the same time, for Polissia, the area with traditional fodder crops and spiked cereals, including winter wheat, decreased (**Fig. 12**).

The climate change signal in Iowa, USA, is quite faint compared to that in this study. Similar to the Polissia zone, the growing season length has increased over the last 30 years. Corn planting date has advanced by 0.13 d yr-1 from 1980 to 2015 due to warming spring temperatures, as determined from the US Department of Agriculture National Agricultural Statistics Service. A trend of increasing spring and summer rainfall and suppression of extreme high temperatures has also been observed. This along with improved genetics and management has resulted in continuously rising corn and soybean yields. Farmer's choice of crops have not changed during this period. These crops have strong markets and genetic improvements have maximized their production potential for existing and evolving conditions.

There are some peculiarities in the distribution of corn and sunflower fields, in western Polissia, which is a cooler territory. Therefore, the increased area under these crops began only in 2016–2018, when the temperature of the growing season approached the optimum for these crops (**Fig. 13**). An important factor in the expansion of sunflower and corn fields in all regions of Polissia is undoubtedly a higher economic return they provide compared to traditional crops. For example, corn yields in Polissia are almost twice as high as winter wheat yields at similar selling prices, providing certain advantages to the rapid increase in its fields, which is especially typical for central and eastern Polissia. The same is true for sunflower. At the same time, there is a tendency towards a decrease in the winter wheat fields (Fig. 12).

The highest profitability in the Ukrainian Polissia zone was achieved while growing sunflower – 5,580 UAH/ha, winter rape – 6,525 UAH/ha, corn for grain – 6,818 UAH/ha, and winter wheat only – 4,161 UAH/ha (Moskalenko, 2015). Thus, over the past 10–15 years, due to the warming of the growing season, the traditional structure of sown areas in the Polissia region has been significantly transformed towards more intensive soil degrading crops and overall more degrading to natural resources and ecosystems of this region.

In this regard, it is important to monitor negative phenomena both on the territory of agricultural land and

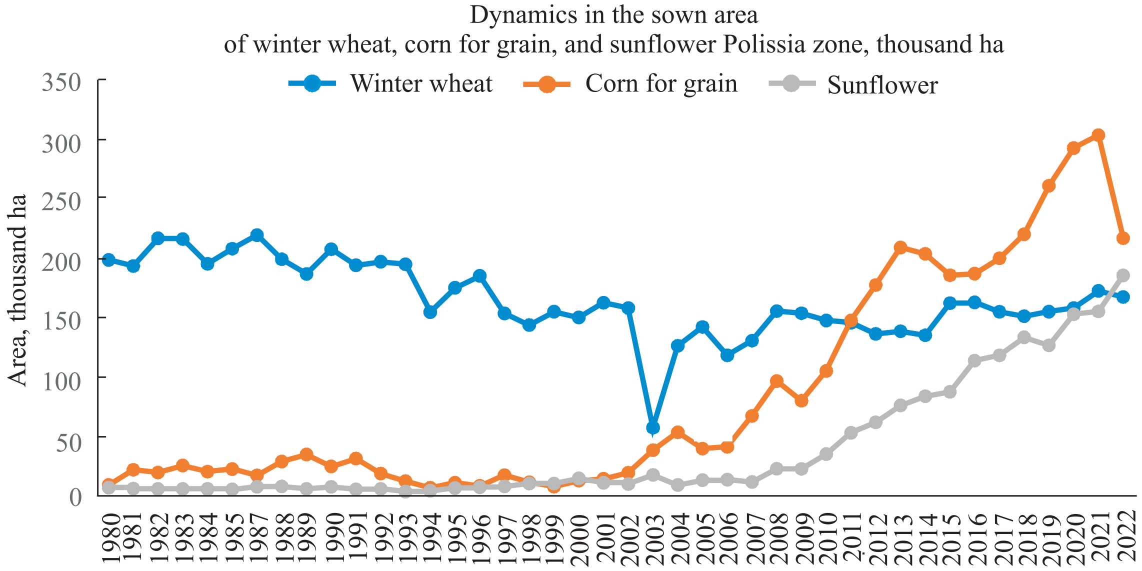

Fig. 12. The dynamics in the sown area of winter wheat, corn, and sunflower on average in the Ukrainian Polissia zone, thousand ha (Built by the authors using the data from the State Statistics Service of Ukraine)

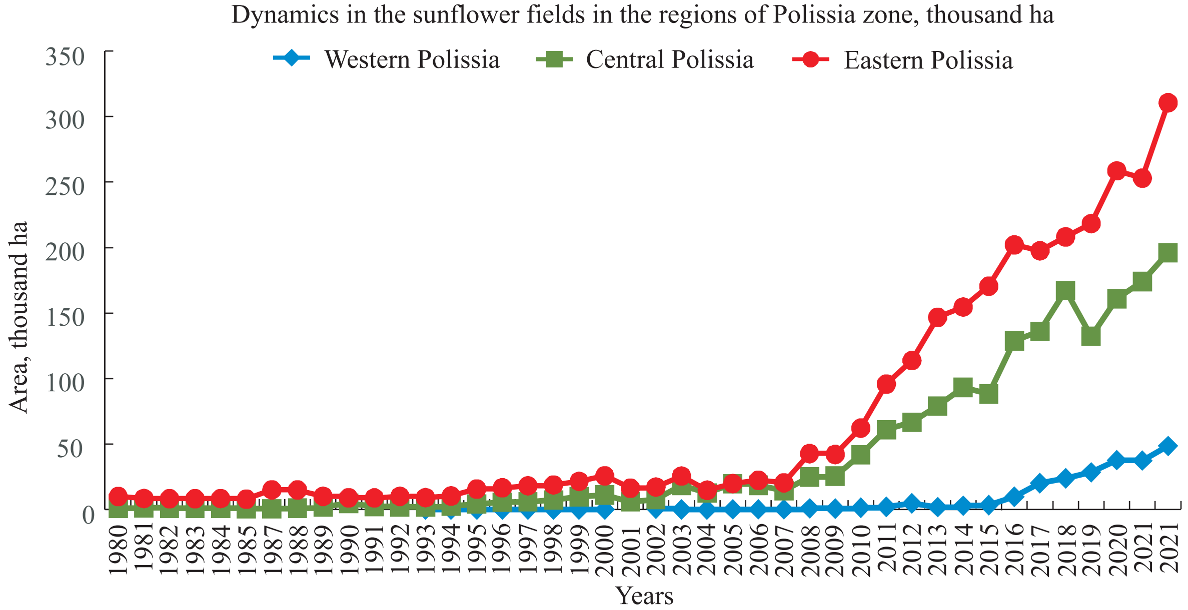

Fig. 13. The area of sunflower fields from 1980 to 2021 for the Polissia regions. (Built by the authors using the data from the State Statistics Service of Ukraine)

natural ecosystems. These include disruption of the optimal regime for providing crops with moisture during the growing season, degradation of mineral and organogenic soils, increased risks of wind erosion (deflation), and a decrease in biodiversity in such ecosystem elements as wetlands and forests. The factors of climate change and economic activity impact ecosystem elements in Ukrainian Polissia are summarized in **Fig. 14**.

Over the latest 30 year period, stress on Iowa soils have remained high (intensive row crop production) with some reduction in tillage intensity being observed and a small increase of cover crop use. Water erosion rates vary considerably across the state depending on topography and rainfall occurrences. However, due to evolving management practices, especially reduced tillage and cover cropping it is difficult to discern a climate change contribution to soil erosion risk.

Satellite monitoring is widely used in many investigations, including the ones on climate change and its impact on ecosystems. A well-known index of the vegetation state, NDVI, for the 30-year-long period

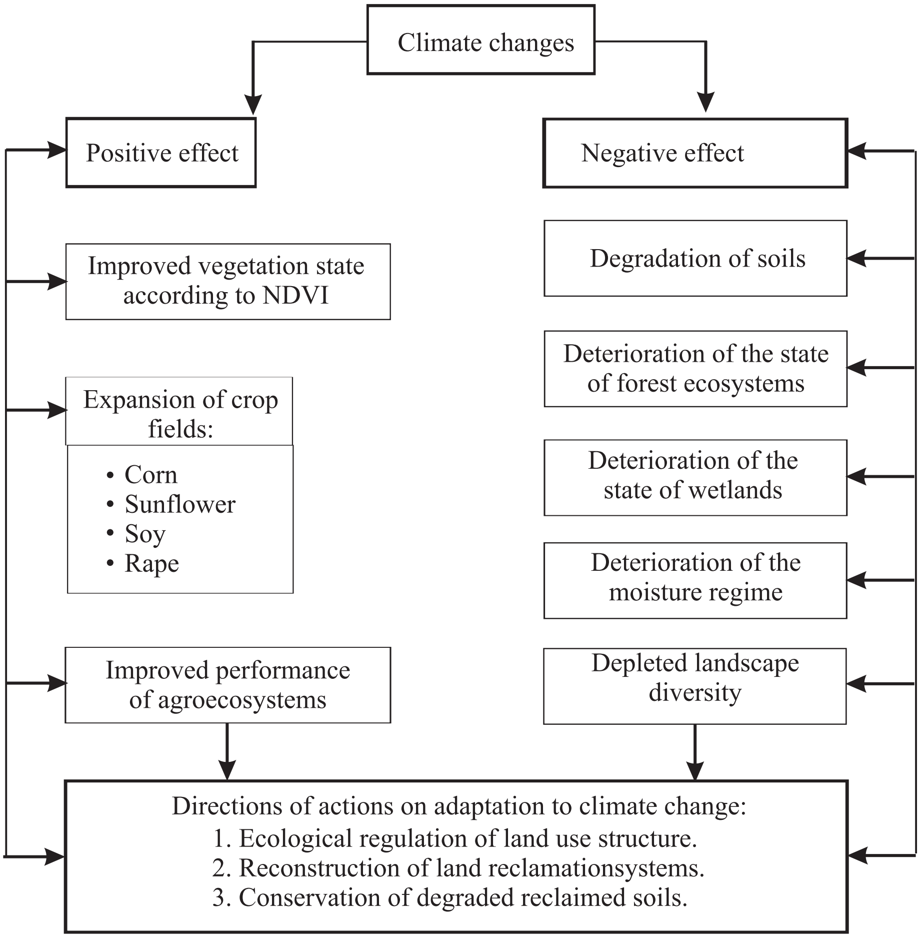

Fig. 14. The consequences of climate changes on agricultural production and ecosystems of Ukrainian Polissia (Source: proposed by the authors)

was used to study the seasonal tendencies in the development of the vegetative cover in Europe using the new product of NDVI time series – TIMELINE NDVI (https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ndvi_time_series/). The long-term dynamics was determined with the resolution of 1 km on across Europe, and specific regional and seasonal patterns (Eisfelder et al, 2023) in the NDVI were found in spring, summer, and autumn for different regions. During the growing period, there were some positive NDVI trends existed for large parts of western, central, and south-eastern Europe in 1989–2018. In its eastern regions, there was also a positive NDVI tendency with time, which is in complete agreement with our results for the territory of Ukrainian Polissia.

Klimavicius et al (2023) used NDVI to determine the change in the growing period indices, including the start, end, maximal development of vegetation, and growing season length. Their association with air temperature and precipitation for 30 years (1982–2015) was identified. The seasonal character of NDVI and long-term trends were analyzed for different types of land utilization: arable lands, pastures, wetlands, mixed and coniferous forests. In the south-western part of the Baltic Sea Region, the growing season lasts the longest, while in the northeast, it is, on average, 10 weeks shorter. Air temperature in February and March is the most crucial factor determining the start of the growing season, while air temperature in September and October determines its end. Precipitation has a much lesser impact on its duration, especially the start of the growing season. At the end of the period under investigation, in 2015, the growing season started earlier and ended later than at the beginning of the investigated period, i.e. in 1982. In general, the duration of the growing season increased by 6–7 weeks. We obtained a similar pattern for the conditions of Ukrainian Polissia. The lengthening of the growing season over the 20-year period (2012–2022) in Ukrainian Polissia for 1982–2011 is within 21–35 days.

However, climate change and the transformation of agricultural production towards increased agro-technogenic cropping system have caused several nega-

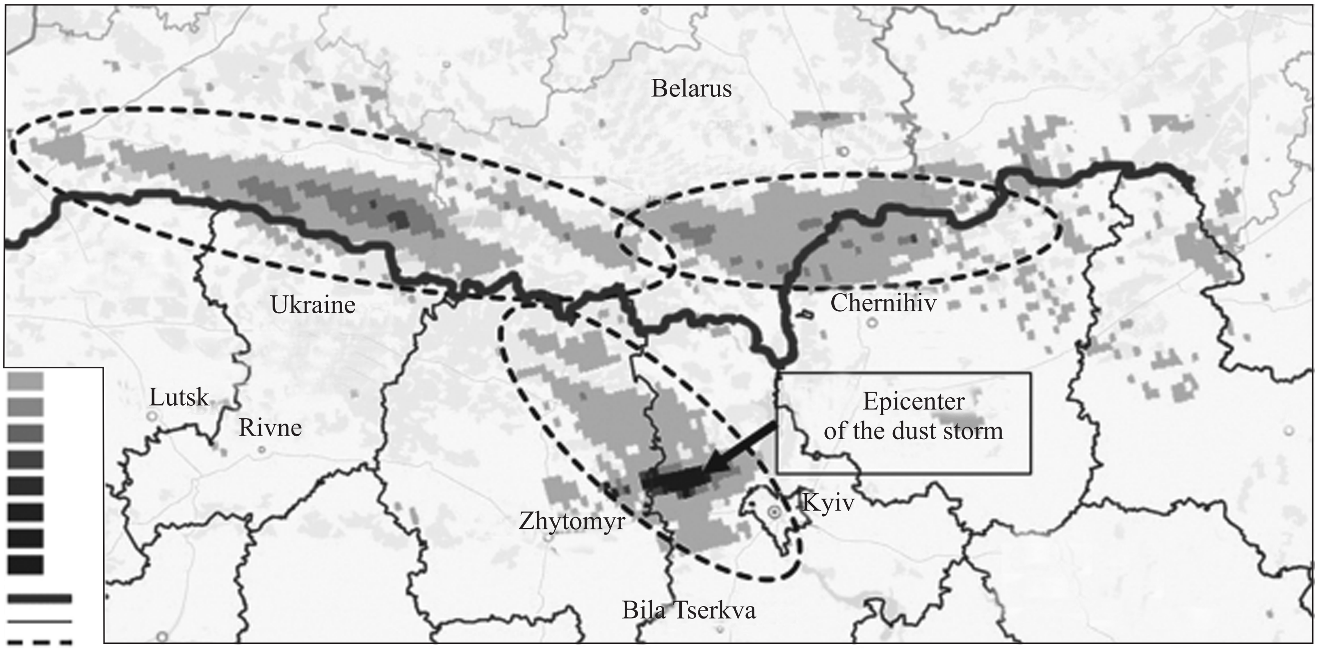

Fig. 15. Dust storm spread over the territory of Ukrainian and Belorussian Polissia according to Sentinel-5P UV Aerosol Index satellite data, 16.04.2020 (Tarariko et al, 2021)

tive impacts on ecosystems that had not been typical for Ukrainian Polissia. For example, while at the beginning of the last century, the number of dry years was only 10 %, over the past 20 years, it has increased to 70 %, and the area with excessive moisture in this zone has shifted to the north and has been preserved mainly within western Polissia (Vergunov, 2022; Sliusar et al, 2023).

The high proportion of crops such as corn and sunflower for which annual tillage is used in modern Polissia crop rotations and the corresponding decrease in the area under fodder crops and perennial grasses have intensified soil degradation. Depending on the granulometric composition, the humus content of turf-podzolic soils ranges from 1.5 to 1.8 %, and the reserves in the arable layer are about 30–40 t/ha, compared to 250–350 t/ha in typical chornozem. With such a low content of organic matter in typical Polissia turf-podzolic soils under such a structure of sown areas, its annual losses of soil organic matter reach 0.5 to 0.8 t/ha, and in crop rotations with an ultra-high proportion of corn and sunflower – up to 0.9 or more (Ryzhuk et al, 2022). Under such conditions, the water holding capacity, physical and chemical properties, and resistance of the surface of turf-podzolic soils to deflation deteriorate. Pre-sowing tillage in spring and the winds of even 10–12 m/s on overdried peatlands create conditions for wind erosion and even large-scale dust storms. The snowless winter, dry spring, and winds of up to 20 m/s in spring 2020 created conditions for a large-scale dust storm that covered most of Ukrainian and Belorussian Polissia, up to 3.5 million ha (**Fig. 15** and **16**, ***a***). Sentinel-5P satellite images showed the epicenter of the storm on the border of Kyiv and Zhytomyr regions, where the maximum concentration of aerosols was observed over an area of about 88 thousand ha. The main factors behind the storm were moisture deficit, soil deflation due to cultivation, high ploughing, low soil erosion resistance, and strong winds (Tarariko et al, 2021). The increasing frequency of dry springs increases the risk of wind erosion, leading to crop damage and air pollution.

The consequences of dust storms in the Ukrainian and Belorussian Polissia, which were contaminated with radionuclides as a result of the Chornobyl accident, are dangerous not only for agricultural production and ecosystems but also for public health due to air pollution with radionuclides. Therefore, it is important to create an anti-erosion structure of landscapes and land use systems in the Polissia region, as well as to increase the erosion resistance of soils by achieving a deficit-free balance of organic carbon and optimal water regime in modern Polissia agroecosystems.

Global climate change is leading to an increase in the occurrence of dust storms and the transfer of erosion material to Ukraine from the African and Caspian deserts, as well as their impact on the growth of wind erosion risks. In the satellite images of Terra/MODIS

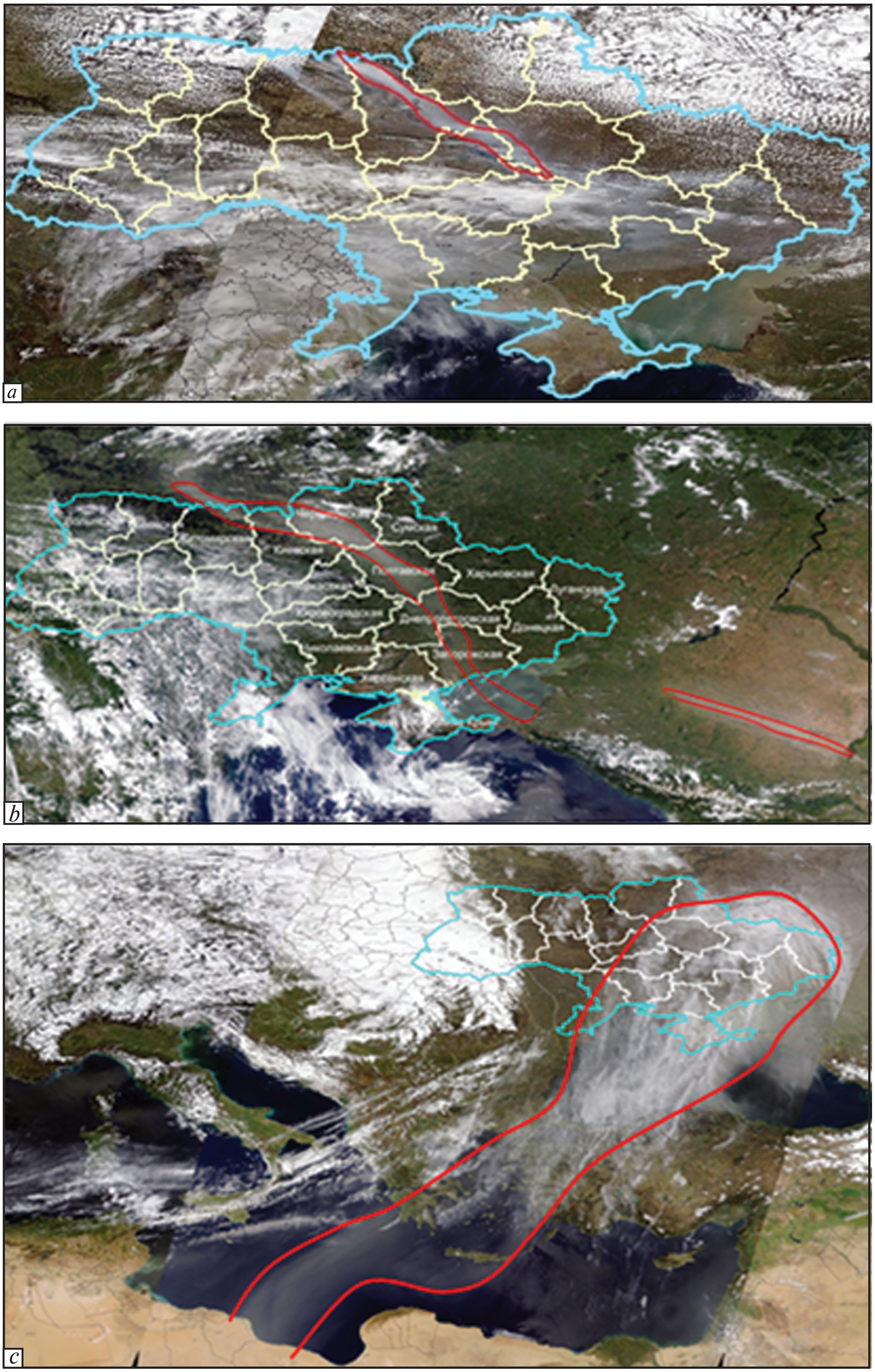

Fig. 16. The manifestations of dust storms and the transfer of erosion material into Ukraine's territory: *a* – April 17, 2020, *b* – June 21–22, 2021, *c* – April 1–2, 2024, according to satellite images of Terra/MODIS, true color images (NASA WorldView, https://worldview.earthdata.nasa.gov/)

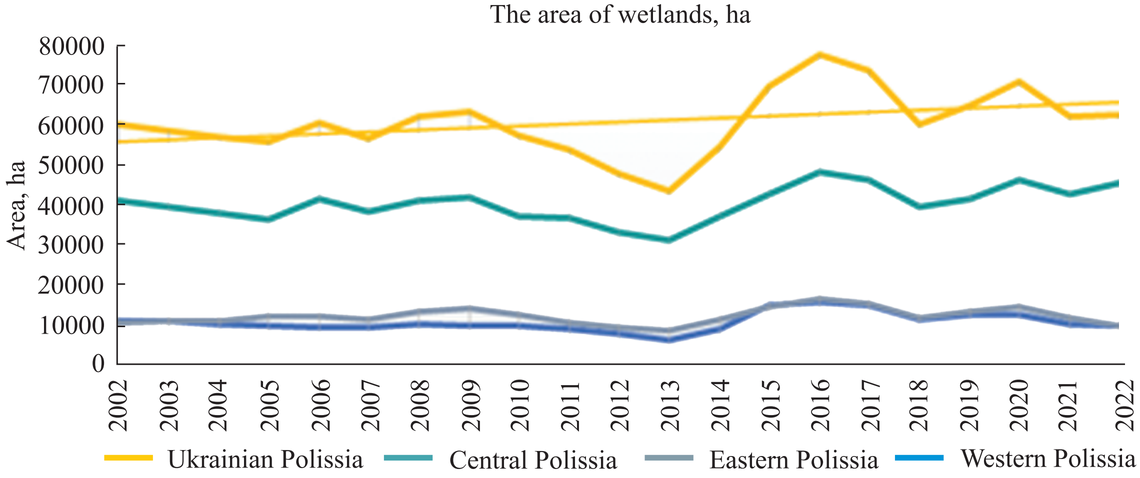

Fig. 17. The dynamics of the wetlands area of Ukrainian Polissia in terms of years and physical-geographical regions

(NASA WorldView, https://worldview.earthdata.nasa.gov/), the method of determining the combined index of the aerosol thickness, which characterizes the degree of obstruction for sunlight to go through the atmosphere, was used to demonstrate a large-scale transfer of erosion material from the Caspian deserts at the beginning of summer, on June 21–22, 2021. As can be seen, the erosion material from the dust storm spread across the Aral Sea and in a 150–200 km wide strip from south to north, reached the city of Kyiv and further into Central Polissia (**Fig. 16, *b***). In the spring of 2024, this phenomenon occurred again but from the African deserts. The satellite image (**Fig. 16, *c***) shows the spread of the dust storm and the transfer of erosion material across the Mediterranean and Black Seas and southern European countries to the territory of Ukraine, including Eastern Polissia (within Chernihiv and Sumy regions).

Based on the satellite data provided, it can be concluded that global climate change has led to an increase in the risks of wind erosion in Polissia, which requires the development and implementation of appropriate comprehensive anti-erosion measures.

An essential element of the ecosystems of Ukrainian Polissia is wetlands, which are reserves of rare flora and fauna (Konishchuk, Smagol, Shumyhai, 2022). Obviously, climate change may have a considerable impact on the area and functioning of wetlands. The results of the study (Xu et al, 2024) made it possible to predict changes in the characteristics of wetlands in North America from 25 to 53 °C north. latitude under two climate scenarios using a modern climate model of the Earth: low emissions of SSP126 with an additional radiative forcing of 2.6 W/m² and high emissions of SSP585 with an additional radiative forcing of 8.5 W/m² by 2100. Across North America, the wetland area is projected to decrease in all seasons in the future, except for winter. These projected seasonal changes lead to a decrease in the average annual wetland area under both the low SSP126 and higher SSP585 emissions scenarios. For instance, based on the forecasts of the multimodal group of projections, the average annual wetlands area in 2071–2100 will decrease by 5.2 % (4.2–7.0 %) and 10.6 % (5.9–13.5%) by the scenarios of SSP126 and SSP585 respectively, as compared to the historic period (1971–2000), since, according to the SSP585 scenario, which presents the upper threshold of the range of scenarios, described in scientific literature (Gao, Sokolov, Schlosser, 2023), the dominating factor for these changes becomes temperature, not precipitation. Wetlands experience significant drying in summer, mainly during the peak of the growing season.

The projected disruptions of wetland seasonal cycles are expected to impact the biodiversity in key wetland habitats in the Upper Mississippi and south-eastern Canada. In addition, wetland areas in colder regions are projected to shrink significantly due to increased infiltration as higher temperatures reduce the presence of ice in the soil (Xu et al, 2023).

Lu et al (2021) found that inland wetlands have significantly declined globally over the past few decades, mainly due to human activities. Global warming (i.e., climate factor) has an additional negative effect on wetland ecosystems by changing their water balance (Zhong et al, 2021), which is also highlighted in a study on predicting the dynamics of their change using a physically based wetland generation scheme in a modern Earth system model (Lu et al, 2021).

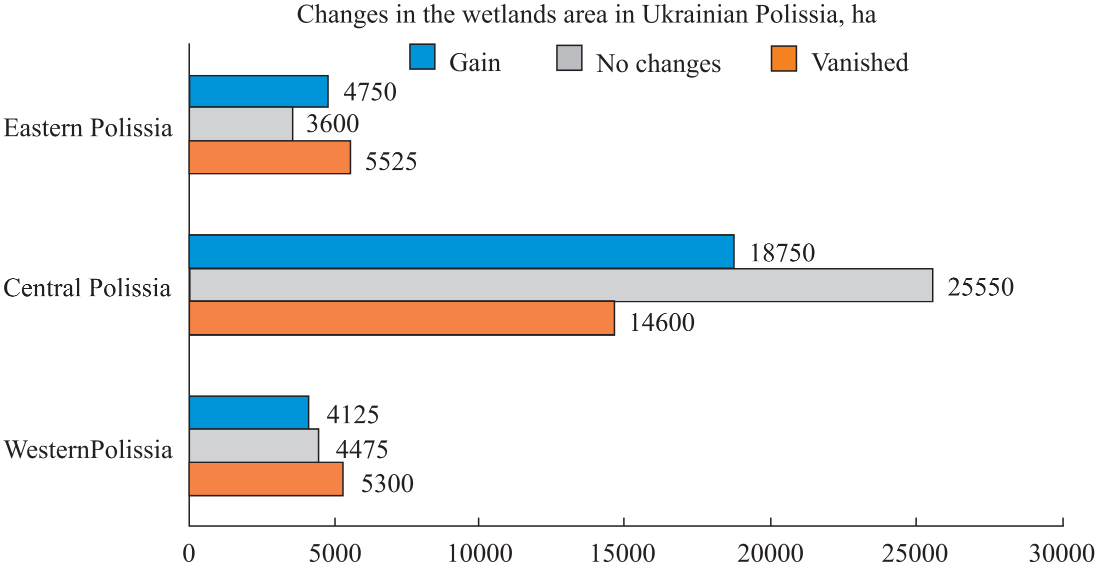

Fig. 18. The diagram of the change in the wetlands area from 2002 till 2022 in terms of physical-geographical regions of Ukrainian Polissia

In Ukraine, the total area of wetlands is about 4.5 million ha (Ivaniuta et al, 2020). They are dominantly located in western Polissia. Yet, overall, in the Polissia zone, including the physical-geographical districts, there is another pattern: since 2002, the area of wetlands has tended to enlarge (**Fig. 17**).

Firstly, as mentioned above, it was caused by the deterioration of the land reclamation drainage infrastructure, which led to the secondary swamping of the reclaimed territories. These territories might require renaturalization or reconstruction of land reclamation systems. But there is both a considerable growth and decrease in the wetlands area depending on the specificities of Polissia zones.

The specificity of western and eastern Polissia is that the area of the vanished wetlands exceeds their growth, while in central Polissia, on the contrary, there is a gain in the wetlands area, probably due to the development of secondary swamping processes (**Fig. 18**). It is obvious that the increase in the wetlands area in central Polissia occurred at the expense of the Chonobyl-affected zone. After the catastrophe at the nuclear power plant, a 30 km deep territory, polluted with radionuclides, was allocated, the borderline perimeter of which is 223.5 km. It was prohibited to have free access to it, to live and thus conduct any economic activities in this territory due to high pollution with radionuclides (Davydchuk et al, 2011). In this zone, there had been several reclamation drainage systems, actively used in agriculture. However, after the suspension of economic activity and relevant management, the reclamation channels started silting in and filling with plants. As a result, the reclaimed territories started gradually returning to their original natural state of wetlands in the course of almost 38 years. Later, on April 26, 2016, the Chornobyl Radiation and Ecological Biosphere Reserve was founded in this territory.

Thus, a dynamic process of both growth and disappearance of wetlands is currently taking place, which depends not only on the warming, climatic features of individual years, but also on the state of the runoff management infrastructure on the territory of reclaimed lands of swamps and river floodplains.

In the process of restoring ecosystems typical for Polissia, it is important to re-naturalize some of the drained swamps and river floodplains. In this regard, it is advisable to use the existing system of land reclamation canals, which can ensure the accumulation of meltwater runoff by maintaining higher water levels in land reclamation canals, which will not only ensure natural conditions for the restoration of swamps by raising groundwater levels but will also contribute to a more rational use of water resources in the territory.

In particular, in the Shatsk Nature Reserve, there is a decrease in the pressure of the Cretaceous aquifer and, accordingly, in the levels of surface and groundwater (Yatsyuk et al, 2021). Such processes lead to a decrease in surface runoff and surface water supply, which is one of the reasons for the shallowing and drying up of small rivers and lakes (Yatsyuk et al, 2019). Thus, in the process of climate warming, there is a decrease in water availability in Polissia, which requires improved water management both in agroecosystems and in landscapes and natural resource management systems in general.

In the ecosystems of Polissia, not only the area and condition of wetlands are changing quite dynamically, but also the structure of forests. There is an increase in fires, damage caused by military operations, and drying out of forests as a result of massive damage by forest pests and diseases (Karamushka et al, 2023; Melnyk and Voron, 2021; FIRMS, 2023). In many cases, considerable drying out of the woods occurs with rather a fast tempo, often during one growing period. A larger number of dry years, including elevated temperatures in spring and summer, has increased the risk of fire and peat fires, which also decreases the area under forests (Karamushka et al, 2023; Melnyk and Voron, 2021; FIRMS, 2023). For instance, within the Narodytskyi district of the Zhytomyr region, 11.5 thousand ha were lost in 2001–2018. In recent years (2016–2018), the losses of the forest cover increased almost three times as compared to the previous ye ars – from 579 ha in 2015 to 1,640 ha in 2016. These losses are most likely associated with a large-scale outbreak of the pest spreading (bark beetle) and subsequent use of sanitary cutting, as well as fires caused by dry weather.

The increase in the number of forest fires, demonstrated by the analysis of the dynamics of burnt forests shown in satellite images (Fig. 11), especially since 2010, may be a consequence of climate change, including rising temperatures and frequent droughts, which create favorable conditions for fires. Several regions, such as Zhytomyr, Kyiv (central Polissia), and Chernihiv (eastern Polissia), showed significant peaks in fire activity in 2002, 2012, 2015, and 2020, which may be indicative of specific weather conditions, such as extreme heat waves or droughts, that contributed to the increased fire risk, as this territory also experiences a more intense temperature increase compared to the regions of western Polissia.

This trend is in line with a general scientific understanding of how climate change can contribute to increased fire risk through higher temperatures and more erratic weather patterns. Continued monitoring and detailed analysis are essential to develop effective strategies for mitigating negative consequences and adapting to new conditions.

In Polish Polissia, there are trends of increasing fire hazards, similar to Ukrainian Polissia (Kolanek et al, 2023), but the scale is slightly different. For example, in 2020, about 60 sq.km of territory burned in the Biebrza National Park, which is significantly less than the peak figures in Ukrainian Polissia. According to the research, the main peaks of fire activity in Polish Polissia are registered in spring and summer. Overall, the situation in Poland demonstrates the increase in fire risks due to climate change, which also requires adapting the fire fighting system.

A negative impact of climate change on coniferous forests is noted starting from the 2000s, which coincides with the period of the most intense warming of the growing season. The latter, along with the trend of decreasing precipitation, has led to the deterioration of hydrological conditions, which, on the one hand, has reduced the biological stability of forests, especially pine forests, and, on the other hand, has improved the conditions for the development of entomophages and especially the bark beetle (Scolytidae). In particular, favorable conditions were created for the development of two or more generations of this pest. As a result, there is a rather large-scale damage to pine forests, loss of their ecosystem functions, landscape, and biological diversity (Moroz, Shumyhai, 2020; Hetmanchuk et al, 2017; Andreieva, 2023). Similar processes of deterioration of pine forests are observed not only in Ukrainian Polissia but also in the USA, Canada, Belarus, and other countries (Hetmanchuk et al, 2017).

It should be noted that many global and regional mathematical models of predicting climate change in the near and distant future and its impact on different kinds of economic activity have already been developed and are under constant improvement (https://worldclim.org/data/cmip6/cmip6climate.html). The most important of them is undoubtedly agriculture, which is related to both food safety and the ecological state of the environment. In our study, we used a satellite information resource in combination with statistical data on the example of the natural geographical zone of Ukrainian Polissia, where the most dynamic, both positive and negative, transformation processes in agricultural production and the environment, in general, are observed under the influence of climate change. The following conclusions have been drawn based on the results of the research.

CONCLUSIONS

Satellite information on climate change and its impact on agricultural production and ecosystems is an essential tool for agro-environmental monitoring and a scientific and methodological basis for developing measures to adapt agricultural production and nature management to climate change.

The 2.2 °C increase in the temperature of the terrestrial surface in Ukrainian Polissia in summer over the past 40 years (1982–2022) has created conditions for an increase in the growing season duration by 21–35 days, which has had a positive impact on the vegetation state during the growing season according to NDVI and the inclusion of corn and sunflower in the structure of sown areas. As a result of a significant increase in their sown areas and high crop yields, Ukrainian Polissia is becoming a new grain and oilseed belt of Ukraine.

Given the current warming of the growing season, transformation of the structure of sown areas, unsatisfactory performance of land reclamation systems to manage water regime in agroecosystems, and the trend of decreasing precipitation, the risks of drought events, soil degradation, spread of wind erosion, and reduction of ecosystem functions and services of wetlands, surface waters, and peat soils are increasing.

There was a tendency towards the extension of the wetlands area, especially from 2015 to 2017. However, the total area of these wetlands in Ukrainian Polissia is quite dynamic, particularly in central Polissia, where both an increase and a decrease in this area are observed. Over the past 20 years, the area of wetlands in this region has increased by 18.7 thousand ha, but at the same time, 14.6 thousand ha have disappeared. The increase in the area of these wetlands, combined with the deterioration of hydrological conditions, is likely to be due to the deterioration of the drainage network infrastructure, leading to secondary waterlogging of reclaimed areas.

If the current rate of warming during the growing season continues and the agro-technological burden on agricultural land resources increases due to the irregular expansion of corn and sunflower fields in crop rotations, the risks of drought events, wind erosion, and soil degradation will increase. At the same time, secondary waterlogging of reclaimed swamps and river floodplains is observed as a result of disruption of the land reclamation infrastructure. Therefore, it is important to develop and implement systemic measures to adapt agricultural production and natural resource management systems to new climatic conditions by forming a balanced structure of land and water use, improving the management of water, physical and agrochemical properties of mineral and organogenic soils, reconstructing existing land reclamation systems to maintain optimal water regime in agroecosystems, and re-naturalizing some part of the secondary waterlogged reclaimed lands, especially those adjacent to nature preservation areas. If such an integrated approach is implemented, the strategic value of Ukrainian Polissia will increase both for agricultural production and its export potential, as well as for the preservation of landscape and biological diversity of unique ecosystems.

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Мета. Встановити закономірності впливу змін клімату у часі і просторі на трансформацію сільськогосподарського виробництва та екосистеми Українського Полісся. **Методи.** Використано супутникові та статистичні да-

ні за останні 40 років (1982–2022 рр.). Середня температура вегетаційного періоду визначалась за сумою радіаційних температур земної поверхні, розрахованих за даними інфрачервоного діапазону (10,3–11,3; 11,4–12,4 мкм) високоточного радіометра AVHRR метеорологічних штучних супутників Землі NOAA, а динаміка опадів за даними ERA5 ECMWF/Copernicus Climate Change Service (https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#description). Вплив змін клімату на стан рослинності та фенологічні параметри, такі як початок, кінець і тривалість вегетаційного сезону, визначались за вегетаційним індексом NDVI (Normalized Difference Vegetation Index), отриманим за даними інфрачервоного (0,72–1,1 мкм) і червоного (0,58–0,68 мкм) діапазонів радіометра AVHRR 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/. Урожайність сільськогосподарських культур і динаміка посівних площ визначались за даними Державної статистичної служби України. Інформацію про динаміку лісового покриву отримано за супутниковими даними Global Forest Watch (https://www.globalforestwatch.org/map/country/UKR). Для оцінки впливу змін клімату на ліси України було проведено дослідження згорілих лісових площ, використовуючи індекс MCD64A1 6.1, розроблений на основі супутникових даних MODIS (https://doi.org/10.5067/MODIS/MCD64A1.061). Для додаткової ідентифікації згорілих ділянок у лісовому покриві було використано дані Hansen Global Forest Change v1.11 (https://doi.org/10.1126/science.1244693). Результати аналізу надали детальну інформацію про площі згорілих лісів у різних областях України за тривалий період. **Результати.** За супутниковими даними радіаційна температура земної поверхні (далі – температура) вегетаційного періоду в середньому на території Українського Полісся за останні 40 років підвищилась на 2,2 °С. Спостерігається регіональна відмінність температурного режиму в напрямку з заходу на схід. На території Західного Полісся підвищення температури земної поверхні за останні десятиріччя становило в межах 1,2–1,6 °С, а у Центральному і Східному – 2,3–2,9 °С. У результаті потепління тривалість вегетаційного періоду подовжилась на 21–35 днів переважно за рахунок настання більш ранньої весни. Спостерігається спадаючий тренд середньорічної кількості опадів до 20–30 мм, що особливо характерно для Центрального та Східного Полісся. Потепління сприяло включенню в структуру посівних площ нових для цього регіону культур, особливо кукурудзи та соняшника, що в цілому позитивно вплинуло на стан рослинності за індикатором NDVI, який в середньому підвищився з 0,30 у 1982–1992 рр. до 0,36 у 2012–2022 рр. Урожайність відповідно також підвищилась і за статистичними даними за останні роки досягла: кукурудзи – 7,0–9,5 т/га, озимої пшениці – 4,5–5,0 і соняшнику – 1,5–2,0 т/га, що наближається до рівня їхньої продуктивності на чорноземах. Разом із тим як за змін клімату так і трансформації сільськогосподарської діяльності зросли ризики погіршення екологічного стану типових поліських ландшафтів, посушливих явищ і деградації ґрунтів. За результатами аналізу двадцятирічної динаміки лісових пожеж найвищі площі згорілих лісів зафіксовані у 2012 (694,30 км²), 2015 (1 078,81 км²) та 2020 роках (776,27 км²), що свідчить про зростання пожежної активності останнього десятиліття. Останнє десятиліття також проявляє тенденцію до подовження пожежонебезпечного періоду. Якщо до 2010 р. найбільші площі згорілих лісів були у березні, квітні, серпні та вересні, то після 2010 р. виявлені також піки у жовтні. Разом із тим спостерігається тенденція збільшення площі водно-болотних угідь, особливо в період 2015–2017 рр. Але в цілому їх площа на території Українського Полісся є доволі мінливою спостерігається як приріст так і зменшення їх площі, що особливо характерно для Центрального Полісся. В цьому регіоні зростання площі водно-болотних угідь за останні 20 років становило 18,7 тис. га. за одночасного їх зниження до 14,6 тис. га. Збільшення їхніх площ, за умови погіршення гідрологічних умов, ймовірно пов'язане з порушенням інфраструктури осушувальної мережі, що призвело до вторинного заболочування меліорованих територій. **Висновки.** Підвищення температури земної поверхні території Українського Полісся впродовж вегетаційного періоду, подовження тривалості вегетаційного періоду, створили умови для включення в структуру посівних площ кукурудзи та соняшнику, що позитивно вплинуло на показник стану рослинності NDVI. В результаті таких перетворень як за площами посіву цих культур так і їхньою продуктивністю зона Полісся перетворюється на новий зерно-олійний пояс України. Разом із тим зросли ризики певної невідповідності можливостей підтримання високої продуктивності агроекосистем і збільшення ризиків розвитку процесів деградації земель, погіршення екологічного стану водно-болотних угідь і лісів, а також обміління та пересихання малих річок і озер. Досягнення рівноваги між підтриманням високої продуктивності сучасних агроекосистем і безпечним природокористуванням потребує розробки та запровадження системних заходів із адаптації сільськогосподарської діяльності та природокористування до нових кліматичних умов, що потребує удосконалення управління земельними, водними та біологічними ресурсами, досягнення оптимальних параметрів родючості мінеральних і торфово-болотних ґрунтів. Необхідною також є реконструкція існуючих меліоративних систем у напрямку формування оптимального водного режиму земель сільськогосподарського призначення й охорони типових поліських екосистем.

Ключові слова: супутникові дані, температура земної поверхні, урожайність, водно-болотні угіддя, вегетаційний період, екосистема, волога, ґрунтовий покрив, ерозія, меліорація, NDVI.

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