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Spatiotemporal patterns and vegetation forecasting of sunflower hybrids in soil and climatic conditions of the Ukrainian Steppe zone

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Abstract. Long-term studies of tillage and crop management are essential in finding out which crop production practices would contribute to sustainable yields and profits. In the conditions of climate change, such issues as selection, forecasting and adjustment of crop cultivation systems in the zone of moisture deficit and agricultural risk management are especially relevant. Therefore, the aim of the study was to establish spatiotemporal patterns of vegetative development of sunflower hybrids and predict their productivity in the soil and climatic conditions of the Ukrainian Steppe. A detailed analysis of seasonal changes in the values of the normalized difference vegetation index in sunflower hybrid crops during the 2019-2021 time period was carried out with the help of space images from the Sentinel 2 satellite device, and then processed with the ArcGis 10.6 licensed software product. The credibility of the achieved results of the condition of crops in different phases of plant vegetation on the basis of *NDVI* and the possibility of their use for forecasting the yield of agricultural crops have been proven. The adjustment capabilities of various sunflower hybrids to the STeppe soil and climate conditions were determined, particularly in regards of such hybrids as Oplot, Hektor, DSL403, P64GE133, 8X477KL. A model of the yield forecasting function for each sunflower hybrid was developed according to the annual level of moisture supply. The level of data approximation of the forecasting models was 97.2-99.9%. It is suggested to use system functional models

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developed specifically for different moisture supply and plant nutrition conditions in order to forecast of the yield of sunflower hybrids according to a particular situation. The results can be used to improve the methodology of researching the vegetation of agricultural crops, to validate crop rotation, to choose the best practical ways for the use of multifunctional growth-regulating substances, to define the climatic adjustment of cultivars and hybrids, to manage resources, to develop adaptive climate technologies in agriculture and crop production, to calculate their efficiency, to forecast the yield and to ensure the profitability of agricultural production in the moisture deficit zone and managing a high-risk farming

Keywords: crop production; climate; remote sensing; satellite images; modeling

INTRODUCTION

Intensive agriculture has greatly increased crop yields but simplified the production due less diverse farming systems, higher genetic homogeneity, and more uniform farming landscapes in recent decades. It should be noted that the system of relations between natural and man-made causes has changed significantly, which leads to a larger number of abnormal climatic conditions and the risks of their negative effects on the conditions for growing agricultural crops. The main result of the global warming is a decreasing moisture supply. Moisture has become a limiting factor for soils in various climatic zones. Therefore, the preservation of soil moisture, increasing the plant stress resistance to moisture deficit, adaptation of cultivars and hybrids to new climatic conditions, the need to adjust crop rotations and agro-technological operations, and the use of effective multifunctional growth-regulating substances have become an urgent issue.

The Steppe as a physico-geographical area characterized with high temperatures, and scarce, unstable and uneven distribution of atmospheric precipitation (Dudiak *et al*., 2019; Zhang *et al*., 2019a), which causes high-risk farming conditions with a possibility of insufficient harvest of agricultural crops (Pichura *et al*., 2021; Mateo-Sanchis *et al*., 2021). Since the 2000s, the number of abnormal climatic conditions has tripled, which caused a rise in the average annual temperature by 2.6°C and a higher number of torrential precipitations in the spring-summer period (Pichura *et al*., 2022). This results in: a decreasing precipitation-productivity (Lisetskii *et al*., 2020; Oti *et al*., 2020), an increase in wind erosion (Dudiak *et al*., 2021), local torrential precipitations and water erosion processes (Özşahin, 2023), as well as higher risks of terrestrial runoff, disruption in transpiration and increased evaporation of moisture in the summer-autumn period, water deficiency for agrocenoses (Assan *et al*., 2020). Under such extreme climatic conditions, moisture is a limiting factor in the productivity of agricultural crops (Török *et al*., 2020), therefore the agrotechnological conservation of pre-sowing soil moisture and the effective use of its reserves during the vegetation period of plants are utterly important (Domaratskiy *et al*., 2020; 2022).

One of the promising areas of agricultural science research is the use of the remote sensing data to study the state of the crops based on the normalized difference vegetation index (*NDVI*) (Ding *et al*., 2022; Essaadia *et al*., 2022). Spatiotemporal differentiation of the agrocenoses vegetation index indicates the state of plant development in different phenological stages depending on the natural and climatic conditions, the scope and kind of precipitation, the degree of agrotechnical measures. This makes it possible to define the level of adjustment of the hybrids to specific climatic conditions of certain physical and geographical zones and to evaluate the yield of agricultural crops.

Therefore, the purpose of the study was to forecast the yield to bolster the agricultural profitability, and to increase the level regional and national food security by rationalizing the optimal complex of agrotechnical measures, the choice of adjustable cultivars and hybrids considering the soil and climatic conditions of the Steppe zone.

LITERATURE REVIEW

Sunflower is the main Ukrainian oil crop, which takes about 25-28% in the structure of farm rotations. The seeds of modern zoned cultivars and hybrids contain 50-52% of oil, and the seeds of selective varieties - up to 60% (Shakalij *et al*., 2019). In comparison to other oil crops, the sunflower provides the highest oil yield per unit area. Sunflower oil makes up for 98% of total oil production in Ukraine. Scientists S.D. Koutroubas *et al*. (2020), A.U. Jan *et al*. (2022) explained that ensuring a high level of oil content in crops requires a high level of moisture supply in the cultivation territory. Y. Cheng *et al*. (2023) found that in arid regions, soil moisture and nitrogen concentration are key indicators of plant development and productivity. During the growing season, the level of water consumption for sunflower changes (Domaratskiy *et al*., 2020): from the emergence emergence to the inflorescence process, plants consume about 20% of growing water; during the phenological stages of fruit formation and flowering, the consumption of total vegetation moisture is 60%. In particular, the studies of V. Giannini *et al.* (2022) established that under the conditions of using standard agrotechnical measures on non-irrigated lands of the Steppe zone, the sunflower yield would not exceed 50% of its biological potential. Scientists I.V. Aksionov *et al.* (2021) emphasized that one of the ways to successfully solve the problem of a high and stable yield is the wide implementation of forecasting methods and programming the yield of agricultural crops. In turn, V.G. Didora *et al.* (2013) in their studies explained the need to use forecasting methods as a tool for solving the task of optimizing agricultural production, including the production of oil crops, as a way of considering and reducing weather risks on the agrocenoses productivity. Scientists P. Kamath *et al.* (2021) and R.J. Chitsiko *et al.* (2022) emphasized that forecasting and planning are among the most accurate measures and methods of scientific prediction, which sums up all types of activities related to defining the state of the agrocenosis of a cultivar or hybrid in future prospect in ways specific for these methods. P. Debaeke *et al.* (2023) notes that crop forecasting several weeks before harvest is strategically important for cooperatives that collect, store and sell grain. Scientific works of Y. Zhang *et al.* (2019b) and G. Ronchetti *et al.* (2023) in particular prove that using of satellite images provides relevant and crucial information, which is used to develop the yield forecasting models regardless of the scope of the research area and crop rotation based on *NDVI* calculation. In modern science, the application of Sentinel satellites has provided a number of new possibilities for yield forecasting due to its spatial resolution and revisit time (Desloires *et al.*, 2023; Zhang *et al.*, 2023).

Based on the results of the analysis of recent studies, it was established that it is important to develop a model for predicting the yield of agrocenoses, including sunflower, based on the *NDVI* index by using the data on the distribution of water consumption and plant nutrients on various development stages.

MATERIALS AND METHODS

The study of the development and productivity of sunflower hybrids in the soil and climatic conditions of the Steppe zone of Ukraine was conducted in the period from 2019 to 2021 at the experimental field of the Mykolaiv State Agricultural Research Station of The Institute of Climate-Smart Agriculture of The National Academy of Agrarian Sciences of Ukraine (Fig. 1). Experiments were conducted without irrigation. The total area of experiments: 2019 – 1.9 ha, 2020 – 8.4 ha, 2021 – 0.75 ha.

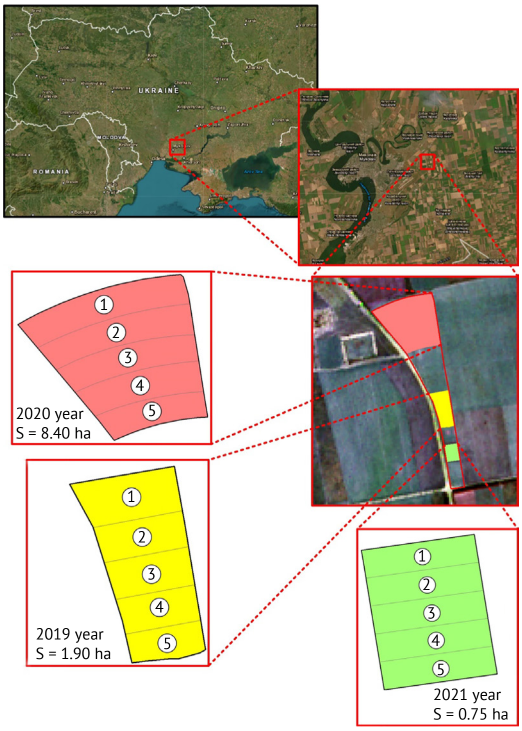

Figure 1. *The location of the experimental fields and the arrangement of sunflower hybrid sowing in the period of 2019-2021*

Notes: *1 – Oplot; 2 – Hector; 3 – DSL403; 4 – P64GE133; 5 – 8X477KL*

Source: *compiled by authors*

The experimental areas are located on low-humus southern chernozems with a loam that has a high level of dust in its granulometric composition. The content of humus in soils varies from 2.7 to 3.1%, the depth of the humus horizon is 30-40 cm. The reaction of the soil solution is close to neutral (pH 6.5-6.8), hydrolytic acidity is within 2.00-2.52 mg equiv. per 100 g of soil. The amount of absorbed bases is 32-35 mg equiv. per 100 g of soil, the degree of saturation with bases is 95.7%. According to the content of mobile nutrients, the soil of the experimental area is characterized by an average content of nitrate-nitrogen in the soil layer 0…20 cm – 30.0 mg/kg, 100 mg/kg of mobile phosphorus and a very high content of exchangeable potassium – 300.0 mg/kg of soil. The data on actual surface air temperature data (*T*, °C) and the amount of atmospheric precipitation (*P*, mm) for the growing season in 2019, 2020 and 2021 was used in the study, while the climatic norms for the research area were based on the data of the Mykolaiv meteorological station for the period of 1970-2020.

Program of scientific research. A field experiment was established in order to study the vegetation process based on the *NDVI* index and establish the climatic adjustment of high-oleic sunflower hybrids of Ukrainian and French selection. The Ukrainian selection included sunflower hybrids Hektor and Oplot (originator – V.Ya. Yuryev Institute of Crop Science). French selection consisted of DSL403 and P64GE133 (produced by Corteva, Brevant) and 8X477KL (produced by Dow Seeds). The experiments were repeated in 2019, 2020 and 2021. In 2019, the sowing date is 04/24, the harvest is 08/26; in 2020: sowing – 29/04, harvesting – 22/08; in 2021: sowing – 10/05, harvesting – 12/09. Every year, sunflower hybrids grew in the same sequence within typical soil and climatic conditions, in an area where the winter wheat used to grow before (Fig. 1). The sown area of the first order lot was 168 m^2, the testing lot was 120 m^2. Sowing was carried out with a UPS-8 pneumatic precision seeder, the seeding rate was 48.7 thousand units/ha. Accounting and observation were carried out according to the methodology of scientific research in agronomy (Ermantraut *et al.*, 2008; Didora *et al.*, 2013), methodological recommendations of The Plant Production Institute named after V.YA. Yuriev of National Academy of Agrarian Sciences of Ukraine (Kyrychenko *et al.*, 2014), DSTU 6068:2008 (2009) and DSTU 7011:2009 (2010). The level of soil moisture was determined by the thermogravimetric analysis during sowing and harvesting (Papish, 2001). The seed yield was recorded manually, with the subsequent calculation of the yield in tons from 1 hectare of the sown area with 8% seed moisture and 100% seed purity.

Methods of deciphering space images and spatial analysis. Spatial-temporal differentiation of the vegetation of sunflower hybrids was determined on the basis of the calculation of *NDVI* (Beyer *et al.*, 2023) based on the data of decoded Sentinel 2 space images with a spatial resolution of 10×10 m per pixel.

The *NDVI* value is calculated by the formula:

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

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

The *NDVI* value ranges from 0 to 1.0. Open field soil is characterized by *NDVI* values from 0.05 to 0.15. At the beginning of the sowing the value of *NDVI* was 0.15 each year. In the period of active vegetation from the macrostages of "flower bud development" (*BBCH* 51-59) to the end of the "blooming" macrostage (*BBCH* 61-69), the *NDVI* value reflects the state of crop development, namely: < 0.15 open soil; 0.15-0.2 – sparse vegetation; 0.2-0.3 – suppressed vegetation; 0.3-0.4 – very poor condition; 0.4-0.55 – satisfactory condition; 0.55-0.7 – good condition; > 0.7 – very good plant condition.

Space photographs with no overcast over the experimental field were used in the research. The frequency of image processing was 10-16 days, which made it possible to determine the *NDVI* value for the main phenological stages of the development of sunflower hybrids, namely: seedlings (*BBCH* 00-09), the first pair of true leaves (*BBCH* 10-12), inflorescence formation (*BBCH* 14-59), flowering (*BBCH* 61-69), ripening (*BBCH* 71-99). The calculation of *NDVI* at all phenological stages made it possible to study the development process of sunflower hybrid crops and establish changes in the terms of the phenological stages of plants in regards to the climatic conditions of the year: dry, moderately humid and wet year. Space images were processed considering the sowing and harvesting dates in 2019, 2020, 2021.

In order to improve the quality of the visualization of maps of the spatiotemporal distribution of *NDVI* values and to increase both the accuracy of the interpretation of the vegetation index within individual plots and the characteristics of the heterogeneity of the vegetation of sunflower hybrids, the interpolation of the values obtained on the basis of the decoding of the Sentinel 2 space images was carried out. The interpolation was carried out using the method of geostatistical analysis with a radial basis function (Chen *et al.*, 2023; Pichura *et al.*, 2023). This method allows to establish an accurate interpolation of surface changes in *NDVI* values while preserving the input raster data.

The raster calculator of the ArcGis 10.6 software was used to calculate the generalized map of $NDVI_{year}$ values of sunflower hybrids based on the *NDVI* raster surfaces of the main phenological stages of vegetation and the formation of plant productivity. The correlation and regression analysis (Grover & Kaur, 2021) was used to develop functions for predicting the yield of sunflower hybrids depending on the spatial-temporal differentiation of the values of the vegetation index.

Space images processing, cartograms constructing, spatiotemporal and correlation and regression analysis were carried out with the licensed software product ArcGis 10.6 and Microsoft Excel 2010. The conducted research complies with all ethical norms according to The Convention on Biological Diversity (2022).

RESULTS AND DISCUSSION

Analysis of climatic research conditions. Climatic conditions of the studied area are characterized as medium-arid. The average statistical value of the normal (in period of 1970-2020) air temperature during the growing season was 18.0°C (Fig. 2a), the standard deviation was 4.9°C, and the level of variation was 27.3%. In particular, the average value of the air temperature during the growing season in the dry year (2020) was 19.0°C, the standard deviation was 6.3°C, and the level of variation was 33.3%. In a moderately humid year (2019), the average air temperature during the growing season was 20.4°C, the standard deviation was 5.5°C, and the level of variation was 27.0%. In the wet year (2021), the average air temperature during the growing season was 18.4°C, the standard deviation was 6.6°C, and the level of variation was 35.8%.

It has been established that over the past 10-15 years, the frequency of abnormal climatic conditions of a torrential nature has increased (Pichura *et al.*, 2022). In July 2020 (Fig. 2b), a drastic rise in the vegetation index was observed during the flowering period (*BBCH* 61-69), but the torrential nature of atmospheric precipitation had no positive outcome or prolonged effect on the formation of the productivity of sunflower hybrids. In particular, in the dry year (2020), a high value of the standard error (84.1 mm) and the level of variation of seasonal changes in atmospheric precipitation (139.7%) were recorded, which confirms their anomaly during the growing season.

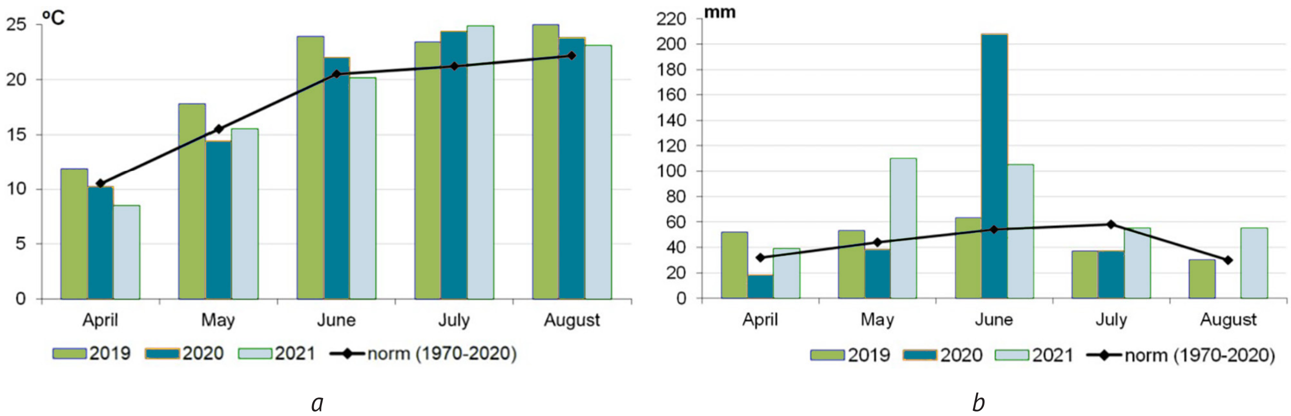

***Figure 2.** Climatic conditions during the sunflower growing season for 2019-2021:*
a – average monthly air temperature (°C); b – amount of precipitation (mm)
***Source:** compiled by authors, based on the data of the Mykolaiv meteorological station*

The average monthly value of atmospheric precipitation during the growing season for 50 years (1970-2020) had been 43.6 mm (Fig. 2b), with the standard deviation 12.6 mm, and the level of variation 28.9%. The year 2019 was close to typical (normal) climatic conditions, the average monthly precipitation during the growing season was 47.0 mm, the standard deviation was 13.3 mm, and the level of variation was 28.3%. A typical wet year of 2021 in the Steppe zone is characterized by an average monthly precipitation of 72.8 mm, a standard deviation of 32.4 mm, and a high level of variation of 44.5%.

Well-developed sunflower crops consume from 500 mm to 600 mm of water during the growing season (Kohan, 2021) (the minimum water requirement is met with 300-400 mm of atmospheric precipitation). During the growing season of 2019, the amount of atmospheric precipitation was 235 mm, in 2020 – 295 mm (in July, an unusually abnormal amount of precipitation was estimated to nake 70.5% of the share of the growing season, being an unproductive precipitation of a torrential nature), in 2021 – 364 mm.

In the arid conditions of the Ukrainian Steppe, the level of soil moisture is a factor that determines the productivity of agrocenoses. It was estimated that 60-70% of the total sunflower water consumption during the growing season are provided by atmospheric precipitation, while 30-40% – by the soil moisture supply (Domaratskiy *et al.*, 2020). Using the thermostatic-weight method, it was established that the pre-sowing moisture reserves in a meter-long soil layer of the experimental fields in the dry year of 2020 amounted to 41 mm, in the moderately humid year of 2019 – 69 mm, and in the wet year of 2021 – 89 mm.

The second half of the growing season in 2019 was characterized by a moisture deficit, being 23.9% less than normal atmospheric humidity, as well as an increase in temperature by 11.5%, which mainly caused stress in plants with a subsequent decrease in productivity. In a dry year of 2020 sunflower hybrids were constantly under stress, caused by a significant deficit of soil and atmospheric moisture in combination with anomalous unproductive rainfall of a torrential nature in July as a result of high air temperature. Peculiarly, in the wet year of 2021, there were no signs of stressful weather conditions and a productive precipitation was recorded during the budding and flowering period (*BBCH* 51-69), which is the defining phenological stage of plant development in crop formation. Therefore, in the conditions of extreme agriculture of the Steppe zone, agrotechnological measures are aimed at preserving moisture.

Studying the state of sunflower hybrid crops. A change in the activity of the plant's photosynthetic processes and the production of chlorophyll content at a certain macrostage and phenological phase are indicators of plant development. The study of changes in the photosynthetic activity of sunflower hybrids was carried out based on the analysis of *NDVI* values, which is common in forecasting the productivity of agrocenoses.

The value of the *NDVI* index within the experimental fields, during 2019, 2020 and 2021, was calculated on the basis of data from satellite images from the Sentinel 2 spacecraft. Using the images, the state of the green mass of plants, which absorbs electromagnetic waves in the visible red range and reflects them in the near infrared was determined. In particular, the maximum absorption of solar radiation by chlorophyll occurs in the red zone of the spectrum (central wavelength of Sentinel 2 – 665 nm), and in the near infrared zone (central wavelength of Sentinel 2 – 842 nm) – the maximum reflection of energy by the cellular structure of the leaf.

The moderately humid year (2019). By interpreting a series of satellite images in a moderately humid year at the beginning of the vegetation process (May 5, 12 days from the sowing date), young seedlings were recorded in sunflower hybrid crops with an average value of the *NDVI* index of 0.26 ± 0.03 and insignificant level of spatial variation – 8.1%. After foliar feeding of the hybrids, a heterogeneous reaction to multifunctional growth-regulating substances was observed, which was later confirmed by satellite images on May 30 (37 days from the sowing date). It should be noted that the growth of Oplot hybrid plants increased and the *NDVI* value varied within 0.54-0.77, the Hector hybrid *NDVI* value varied within 0.54-0.80 and the DSL403 hybrid – within 0.51-0.78. A downward reaction to re-regulating substances was observed in hybrid P64GE133 with an *NDVI* value of 0.41-0.67 and hybrid 8X477KL with an *NDVI* value of 0.43-0.62. At the end of the phenological phase of "inflorescence formation" on June 14 (52 days from the date of sowing) and the beginning of the "flowering" phase on June 19 (57 days from the date of sowing), good (0.55-0.70) and thriving state of vegetation was recorded of all sunflower hybrids (> 0.70). During this period, the average value of *NDVI* was 0.72 ± 0.06, the level of spatial heterogeneity was 8.2%.

The second half of the growing season of sunflower hybrids in 2019 includes the second half of the flowering phase (*BBCH* 67-69) and the macrostages of "fruit formation" (*BBCH* 71-79), "fruit and seed ripening" (*BBCH* 80-89) and "senescence" (*BBCH* 92-99), which are components of the phenological stage of ripening (*BBCH* 71-99). It should be noted that the second period of plant vegetation was characterized by stressful conditions caused by the lack of moisture and high temperatures. This led to the sharp deterioration of photosynthetic processes and the shortening of the "fruit formation" period. On July 4 (72 days from the date of sowing), the average value of *NDVI* was recorded – 0.63 ± 0.09 with noticeable manifestations of heterogeneity in the formation of productivity of sunflower hybrids, the level of spatial variation – 14.1%. During the vegetation period on the "fruit and seed ripening" macrostage, on July 24 and August 13, rapid seed maturation of P64GE133 and 8X477KL hybrids was recorded. In the macro stage of "senescence" from the period of full ripeness (seed moisture about 10%, *BBCH* 92) to harvest (August 23), the average *NDVI* value was 0.37, on August 26 it was 0.30.

The dry year (2020). In 2020, the recorded conditions were extremely dry for the cultivation of sunflower hybrids, which caused a shorter growing season and the terms of individual phenological phases of plants. In particular, the beginning of the growing season in 2020 was characterized by a low level of soil moisture and a small amount of precipitation. This resulted in weaker plant seedlings and a critically low level of photosynthetic processes at the beginning of the phenological phase of inflorescence formation. After the cultivation of crops when the 6-8 true leaves were formed, the delayed reactions of all hybrids to the action of multifunctional re-regulating substances were recorded, as a result of stressful climatic conditions. According to the satellite image decoding data for May 19 (21 days after sowing), a low level of *NDVI* value was calculated - 0.23±0.02 with an insignificant level of variation - 8.2%. The lack of precipitation caused further suppression of plant development, which was confirmed by the results of interpreting the satellite image from June 8 (41 days after sowing), the *NDVI* value was 0.36±0.04 with a significant level of variation - 10.3%. June 2020 was characterized by heavy rainfall, which improved photosynthetic processes in sunflower hybrids. At the beginning of the flowering phase, on June 23 (56 days after sowing), the *NDVI* value was 0.70±0.03 with a slight variation of 4.9% (See Fig. 3; Fig. 4).

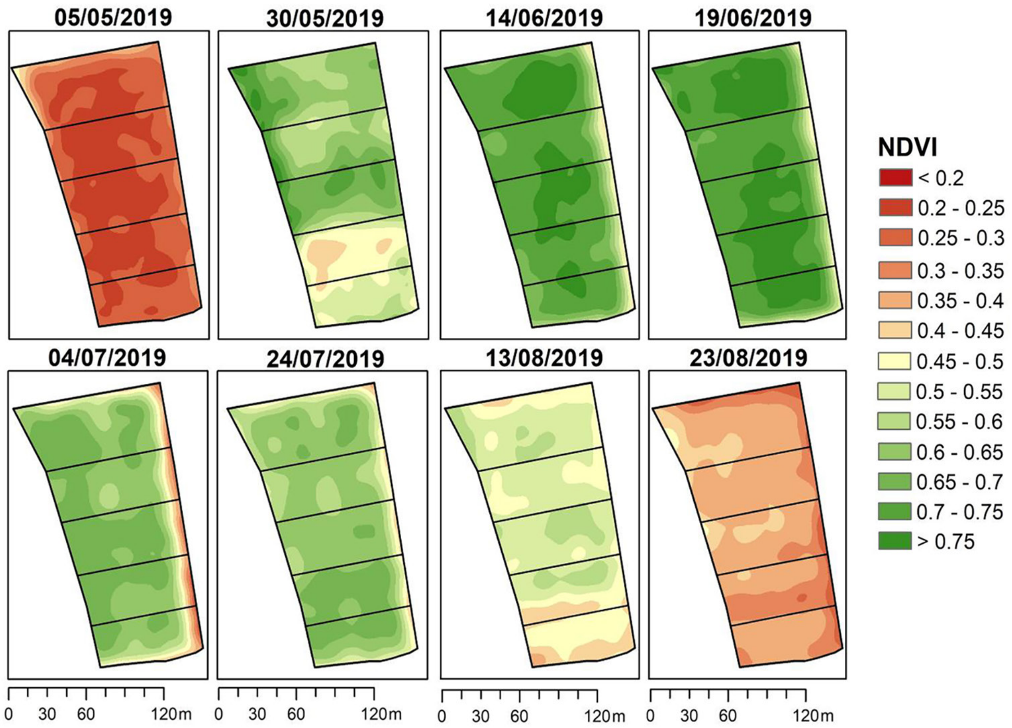

***Figure 3.** Seasonal distribution of NDVI of sunflower hybrids on the experimental field (2019)*
***Source:** compiled by authors*

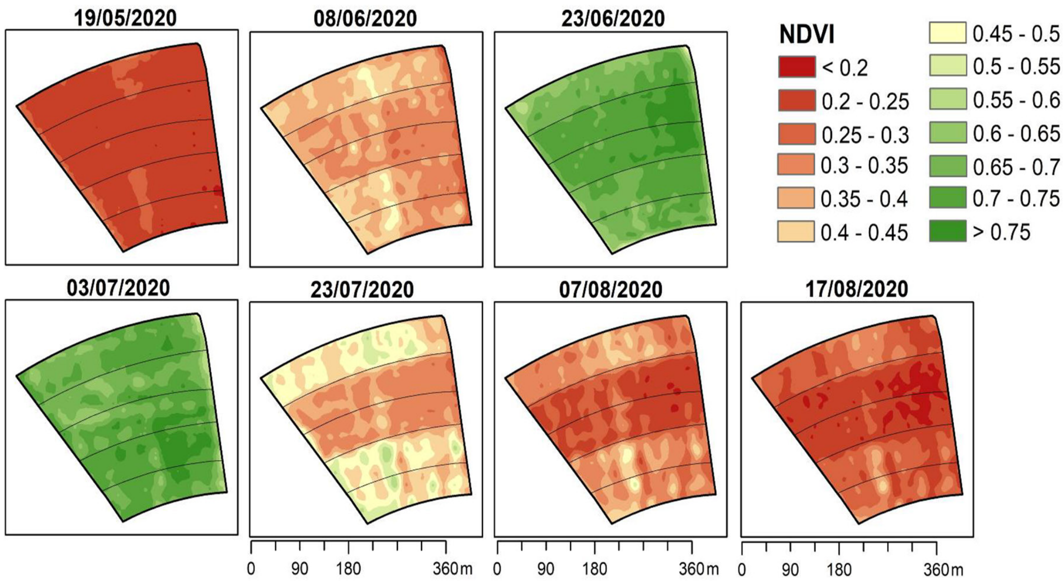

***Figure 4.** Seasonal distribution of NDVI of sunflower hybrids on the experimental field (2020)*
***Source:** compiled by authors*

The end of the flowering phase in July 3 (56 days after sowing), was also characterized by high *NDVI* values of 0.69 ± 0.03 with a variation level of 9.8%. The lack of atmospheric and soil moisture supply in the second half of the plant growing season caused a sharp decrease in the photosynthetic activity of sunflower hybrids and, with a corresponding reduction in the term of the "fruit formation" (*BBCH* 71-79), stimulated the acceleration of "fruit and seed ripening" (*BBCH* 80-89) and "senescence" (*BBCH* 92-99) of plants, on July 23 (86 days after sowing), the *NDVI* value was 0.41 ± 0.04 with a variation level of 9.8%. As of August 7 (101 days after sowing), the *NDVI* value was 0.30 ± 0.04 with a high level of variation – 12.2%.

On August 17-18 (112 days after sowing), during the "senescence" macrostage, the *NDVI* value was 0.25 ± 0.03 with a high level of spatial variation – 11.6%. High spatial variation was caused by significant spatial heterogeneity of plants as a result of stress caused by climatic conditions. It was found that Hektor and DSL403 sunflower hybrids matured faster in dry periods. The lack of moisture caused the deterioration of photosynthetic processes, a significant decrease in the content of chlorophyll in plants, a shortening of the terms of important phenological phases and the vegetation period of sunflower hybrids as a whole.

The wet year (2021). The beginning of the growing season in 2021 was characterized by favorable climatic conditions in the pre-sowing period, which ensured a high level of soil moisture during the sowing period. This determined the high energy and uniformity of seedlings, recorded on May 14 (5 days from the sowing date), the value of the NDVI index – 0.25 ± 0.03, the level of spatial variation – 6.2% (Fig. 5).

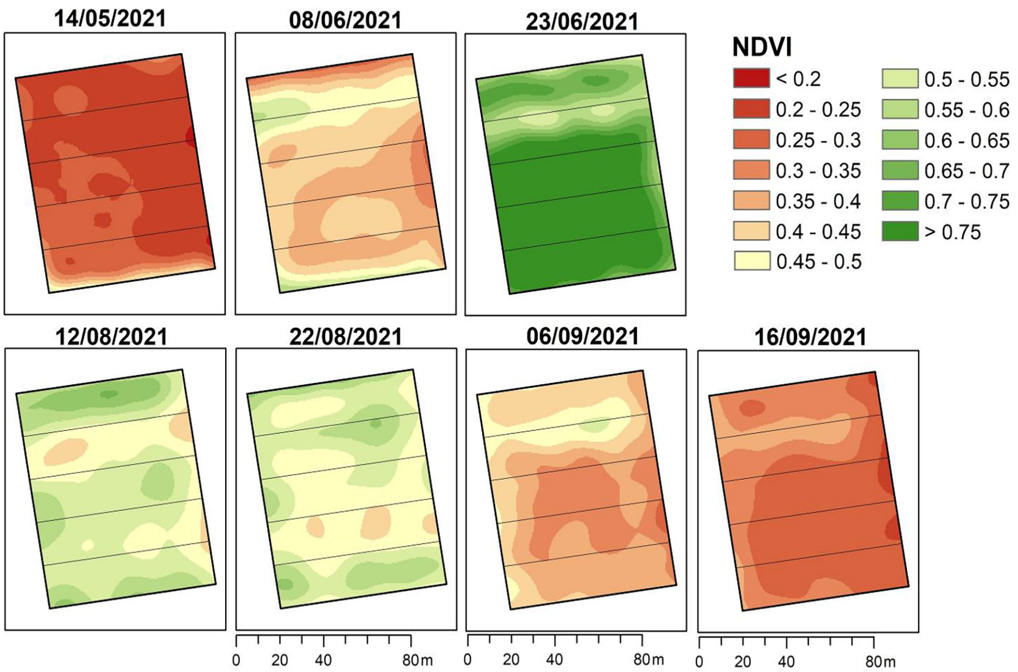

Figure 5. *Seasonal distribution of NDVI of sunflower hybrids on the experimental field (2021)*
Source: *compiled by authors*

On June 8 (21 days from the date of sowing), after processing the crops, a high heterogeneity of the response of the hybrids to multifunctional re-regulating substances was observed, this is due to the redistribution of moisture in the field and the hybrids' adjustment to the climatic conditions of the Steppe. The value of NDVI was 0.42 ± 0.04 with a high level of spatial variation of 14.0%. During this period, the high photosynthetic capacity of the Oplot hybrid was recorded, the *NDVI* value reached the level of 0.56. Hybrids DSL403 (*NDVI* – 0.39) and P64GE133 (*NDVI* – 0.40) had a relatively low level of photosynthesis.

On June 23 (45 days after sowing), during the flowering phenological stage, all the sunflower hybrids were characterized by a high level of photosynthetic processes, the *NDVI* value was 0.75 ± 0.06 with a spatial variation of 8.5%. Systematic and productive atmospheric precipitation and high soil moisture supply in the first part of the vegetation period led to the prolongation of the phenological stage of flowering, which contributed to the increase in plant productivity. In 2021 the flowering phase had lasted for 33 days, which is 2.3 times longer than in the previous two years. The maximum value of *NDVI* during the flowering period is 0.89-0.93. A high level of *NDVI* was recorded in the phenological stage of the "fruit formation" macrostage – 0.74 (76 days from the date of sowing) and the macrostage of "fruit and seed ripening" – 0.54 (95 days from the date of sowing).

A high level of moisture supply, the extension of the duration of the flowering phase provided favorable conditions for the formation of fruits and ripening of sunflower seeds. On September 6 (119 days after sowing), at the end of the "ripening fruit and seed" macro-stage, the *NDVI* value was 0.39; on September 12, in the "senescence" and harvest macro-phase, the *NDVI* value was 0.32. Spatial variation during the growing season of plants was caused by spatial differentiation of soil moisture and different levels of plasticity of hybrids to the climatic conditions of the Steppe zone.

Forecasting the yield of sunflower hybrids. Sunflower has a deep root system and the ability to consume water from a depth of 2 to 4 meters in dry years, however it still needs moisture supply. In different periods of the phenological stages of development, the sunflower consumes moisture unevenly, most actively during the phase of intensive growth, flowering and seeding. From the seedlings emergence (*BBCH* 09) to the inflorescence formation (*BBCH* 15), plants consume about 20% of vegetation moisture; during the phenological phases of inflorescence formation (*BBCH* 16-59) and flowering (*BBCH* 61-69), the consumption of total vegetation moisture is 60%, this period is crucial in the formation of productivity; on the other hand, 20% of vegetation moisture is consumed during the fruit formation and at the beginning of ripening (*BBCH* 71-80).

Defining the *NDVI* index during the main stages of sunflowers' moisture supply and mineral nutrition provided the possibility of creating a general cartogram of the spatial distribution of the vegetation index values in 2019, 2020 and 2021. Generalized cartograms of $NDVI_{year}$ values are the sum of raster surfaces of differentiation in NDVI values in the main periods of plant vegetation. The first raster surface in particular identifies the NDVI values at the beginning of the formation of embryo baskets in the macrophase *BBCH* 16-19, the second raster surface contains the *NDVI* values of the characteristics of the macrophases *BBCH* 61-67, the third raster surface contains the distribution of *NDVI* values of the macrophase *BBCH* 79-80. The corresponding *NDVI* raster is assigned a weighting factor of the cumulative influence of the values of vegetation moisture consumption and mineral nutrition elements on the formation of crop yield. Thus, the values of the raster surface $NDVI_{BBCH\ 16\text{-}19}$ are assigned a weighting factor of 0.2, the values of $NDVI_{BBCH\ 61\text{-}67}$ are assigned a weighting factor of 0.6 and the values of the raster surface $NDVI_{BBCH\ 79\text{-}80}$ are assigned a factor of 0.2.

The generalized map of *NDVI* values is created by the formula:

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

Spatial differentiation of $NDVI_{year}$ values, which are functionally correlated with spatial variation of yield of sunflower hybrids, was calculated using a raster calculator (Fig. 6). It was determined that in the moderately humid year of 2019, the value of $NDVI_{year}$ varied within 0.57-0.69, in the dry year of 2020 – 0.48-0.59, in the wet year of 2021 – 0.49-0.71. It was established that the values of the vegetation index reflect photosynthetic processes and the production of chlorophyll content, which depend on the conditions of moisture supply of the year and the amount of mineral nutrients, but do not identify the overall features and hybrids' adjustment to the soil and climatic conditions of physiographic zones. Therefore, in order to clarify the correlation between $NDVI_{year}$ values to the productivity of individual hybrids, the generalization of $NDVI_{year}$ values was carried out by mathematically relating the raster values of the vegetation index to its average value of the corresponding year.

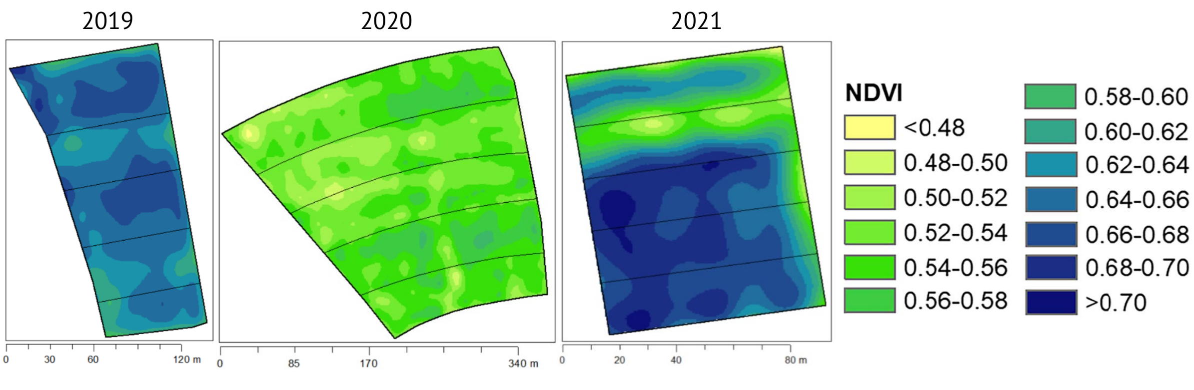

Figure 6. *Spatial differentiation of generalized* $NDVI_{year}$ *values of sunflower hybrids in 2019-2021*
Source: *compiled by authors*

With the calculations, raster surfaces were created, where the value "1" corresponds to the average value of $NDVI_{year}$ for each particular year. Thus, the average value of $NDVI_{year}$ of a separate lot corresponds to the average yield value of the respective sunflower hybrid. Next, the average yield of each sunflower hybrid was calculated: Oplot in 2019 – 3.0 t/ha, in 2020 – 2.01 t/ha, in 2021 – 3.04 t/ha; Hector in 2019 – 2.05 t/ha, in 2020 – 1.65 t/ha, in 2021 – 2.16 t/ha; DSL 403 in 2019 – 2.53 t/ha, in 2020 – 1.88 t/ha, in 2021 – 2.77 t/ha; P64GE133 in 2019 – 2.83 t/ha, in 2020 – 1.96 t/ha, in 2021 – 3.02 t/ha; 8X477KL in 2019 – 2.32 t/ha, in 2020 – 1.71 t/ha, in 2021 – 2.82 t/ha.

Based on the aforementioned data, cartograms of the spatial differentiation of yield of sunflower hybrids were constructed (Fig. 7), correlating to the distribution of generalized $NDVI_{year}$ values according to the formula:

$$CY_{year} = \frac{NDVIi_{year}}{Aver(NDVIi_{year})} \cdot Aver(CY_i), \qquad (3)$$

where, $NDVI_{iyear}$ – the value of the vegetation index within the experimental lot of a separate cultivar or hybrid of a culture; $Aver\ (NDVI_{iyear})$ – the average value of the vegetation index within the experimental plot of a separate variety or hybrid of a culture; $Aver(CY_i)$ – the average value of the productivity of a separate variety or hybrid of a culture within the experimental area.

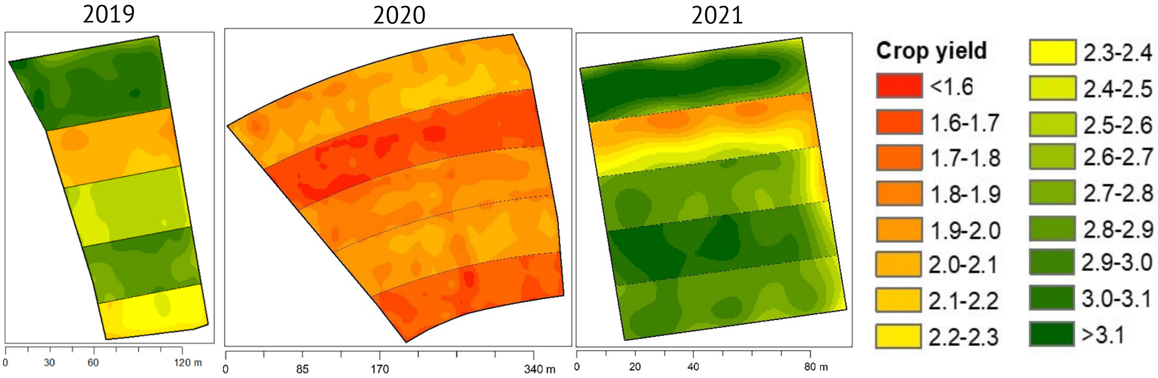

Figure 7. *Cartograms of the distribution of the yield of sunflower hybrids in 2019-2021*
Source: *compiled by authors*

Yield cartograms make it possible to establish the spatiotemporal heterogeneity of the productivity for an individual sunflower hybrid depending on the climatic conditions in 2019, 2020 and 2021. In the average humid year (2019), the yield of sunflower hybrids ranged from 1.86 to 3.18 t/ha. The minimum yield values were recorded for Hector hybrids were 1.86-2.15 t/ha, for 8X477KL – 2.10-2.42 t/ha, average yield levels for DSL 403 – 2.44-2.60 t/ha, while other have reached their maximum yield: Oplot – 2.70-3.18 t/ha and P64GE133 – 2.65-2.92 t/ha. In the dry year (2020), hybrids Hektor – 1.53-1.76 t/ha and 8X477KL – 1.58-1.81 t/ha had the minimum yield values, hybrids DSL 403 – 1.75-2.00 t/ha, P64GE133 – 1.80-2.06 t/ha and Oplot – 1.85-2.16 t/ha. In the wet year (2021), the Hektor hybrid had the minimum yield value – 1.82-2.56 t/ha, the average yield level was recorded in the hybrids DSL 403 – 2.65-2.93 t/ha and 8X477KL – 2.50-2.98 t/ha, the maximum level was achieved by hybrids Oplot – 2.60-3.37 t/ha and P64GE133 – 2.80-3.17 t/ha. It was established that each sunflower hybrid has individual genetic features of plant adjustment to the soil and climatic conditions of the Steppe, which determines the yields. Therefore, a model of the yield prediction function was developed for each hybrid (Table 1).

Table 1. *Forecasting functions and graphs of the normal yield distribution of sunflower hybrids according to the 2019-2021 data*

Oplot
2019 (the average humid year) $Y = 0.914NDVI_1 + 2.739NDVI_2 + 0.923NDVI_3$, $r^2 = 0.996$ 2020 (the dry year) $Y = 0.745NDVI_1 + 2.235NDVI_2 + 0.745NDVI_3$, $r^2 = 0.999$ 2021 (the wet year) $Y = 1.038NDVI_1 + 3.114NDVI_2 + 1.038NDVI_3$, $r^2 = 0.999$

Table 1, Continued

Hector
2019 (the average humid year) $Y = 0.628NDVI_1 + 1.807NDVI_2 + 0.731NDVI_3$, $r^2 = 0.988$ 2020 (the dry year) $Y = 0.585NDVI_1 + 1.841NDVI_2 + 0.624NDVI_3$, $r^2 = 0.972$ 2021 (the wet year) $Y = 0.619NDVI_1 + 2.166NDVI_2 + 0.795NDVI_3$, $r^2 = 0.996$
DSL 403
2019 (the average humid year) $Y = 0.758NDVI_1 + 2.220NDVI_2 + 0.798NDVI_3$, $r^2 = 0.989$ 2020 (the dry year) $Y = 0.701NDVI_1 + 2.107NDVI_2 + 0.703NDVI_3$, $r^2 = 0.999$ 2021 (the wet year) $Y = 0.839NDVI_1 + 2.464NDVI_2 + 0.833NDVI_3$, $r^2 = 0.987$
P64GE133
2019 (the average humid year) $Y = 0.857NDVI_1 + 2.644NDVI_2 + 0.974NDVI_3$, $r^2 = 0.999$ 2020 (the dry year) $Y = 0.704NDVI_1 + 2.111NDVI_2 + 0.704NDVI_3$, $r^2 = 0.999$ 2021 (the wet year) $Y = 0.878NDVI_1 + 2.706NDVI_2 + 0.917NDVI_3$, $r^2 = 0.980$
8X477KL
2019 (the average humid year) $Y = 0.944NDVI_1 + 2.140NDVI_2 + 0.583NDVI_3$, $r^2 = 0.990$ 2020 (the dry year) $Y = 0.629NDVI_1 + 1.887NDVI_2 + 0.629NDVI_3$, $r^2 = 0.999$ 2021 (the wet year) $Y = 0.845NDVI_1 + 2.535NDVI_2 + 0.845NDVI_3$, $r^2 = 0.999$

Source: *compiled by authors*

Functions with a high level of approximation (r^2) describe the spatiotemporal processes of vegetation formation of yield for each individual sunflower hybrids according to the level of moisture supply during the year. Function models were created on the basis of three raster periods of water supply and mineral nutrition of plants. The $NDVI_1$ value contains the average value or the raster surface of the spatial distribution of the vegetation index of sunflower hybrids in the macrophase of the formation of the embryo inflorescences of the *BBCH* 16-19 plant, the $NDVI_2$ value contains the average value or the raster surface of the spatial distribution of the vegetation index of sunflower hybrids in the flowering macrophase of *BBCH* 61-67, the $NDVI_3$ value contains the average value or raster surface of the spatial distribution of the vegetation index of sunflower hybrids at the end of the macrophase of fruit formation and the beginning of seed ripening (*BBCH* 79-80). These functions provide a level of approximation of actual data with 97.2-99.9% level of data approximation, which confirms the high accuracy of predicting the yield of sunflower hybrids.

It should be mentioned that the scientific research in the field of agriculture and crop production S.M. Shakalij *et al.* (2019) and S.D. Koutroubas *et al.* (2020) are approximated and do not take into account the causality of the spatiotemporal differences in the vegetation of varieties and hybrids of crops in regards to the unified *BBCH* scale. Therefore, the researchsuggests to take into account the peculiarities of the vegetative development of different sunflower hydrides according to the unified *BBCH* scale. This made it possible to establish regularities in the formation of the productivity of agrocenoses depending on their development in the main phenological phases and to determine the genetic features of the climatic plasticity of each sunflower hybrid to the conditions of their cultivation in the Steppe zone of Ukraine.

In the studies by I.V. Aksionov *et al.* (2021) and P. Kamath *et al.* (2021) forecasting the yield of agricultural crops was carried out on the basis of correlation and regression analysis, which involves determining the influence of individual natural and agrotechnical factors and further developing regression models of correlation between the actual yield and production factors. Such models are based on field, experimental and official data of institutions monitoring the natural and climatic conditions of the research region and do not take into account the spatiotemporal patterns of plant development in separate phenological phases of their development. Therefore, the author's approach to the development of regression models for predicting sunflower yield based on the new *NDVI* according to the unified *BBCH* scale is proposed. This would allow to quickly react to the changes on the plant vegetation state and to make adjustments to agrotechnical processes in order to increase the productivity of agrocenoses.

In the scientific works of G. Ronchetti *et al*. (2023) and Desloires *et al*. (2023) prove the relevance of using satellite images for forecasting and improving the mechanism of managing the agrocenoses development within a separate field. Thus, taking into account the existing developments, the approaches of using a series of satellite images for detailed research and establishment of spatiotemporal regularities in vegetation and the formation of agrocenoses productivity, considering their genetic features, zonal phytopotential, soil, local nature and climate conditions and elements of varietal agricultural technology, has developed and improved significantly.

The previous scientific works and the original research confirm the scientific and practical value of using modern technologies of remote sensing to improve the monitoring of crops, manage and determine the efficiency of agrotechnical measures, increase the reliability of forecasting the agrocenoses productivity within a specific field or the area of individual agricultural producers. The presented results are particularly aimed at determining the sunflower cultivars and hybrids, which would be the most adjustable to the soil and climatic conditions of the Steppe zone, and defining the specific features and effective ways to use chemical and biological multifunctional re-regulating substances to increase the plants' stress resistance to climate changes and moisture deficit. This enables the land users to adjust the system of growing agricultural crops in the zone of moisture deficit and to manage high-risk farming in order to ensure the profitability of production.

CONCLUSIONS

By interpreting the Sentinel 2 satellite images and analyzing of seasonal changes in *NDVI* values, the spatiotemporal patterns of the sunflower hybrids vegetation and their adjustment to the soil and climatic conditions of Ukrainian Steppe zone were established. A series of maps of with the differentiation of *NDVI* values at every phenological stage was developed, which made it possible to study the development process of sunflower hybrid crops and to establish changes in the length of the phenological stages of plants according to the climatic conditions of the respective year: the dry, the average humid and the wet year. In the average humid (2019), favorable conditions for plant development were recorded in the first half of the growing season, while the second half of the growing season was characterized by a decrease in soil moisture and a shortening in the flowering stage of sunflower hybrids. It was proved that in the dry year (2020) there was a reduction in the length of the flowering stage of sunflower hybrids, a low level of the *NDVI* vegetation index was recorded in the phase of inflorescence formation (0.22-0.40) and the ripping stage (0.30-0.40). In the wet year (2021), a prolongation of the flowering stage and a high value of the vegetation index during all the phenological stages of plant development were recorded. It was established that each sunflower hybrid has individual genetic features of plant adjustment to the Steppe soil and climatic conditions, which determines the yield of the crop. A high level of adjustment was observed in: sunflower hybrid Oplot with an average annual yield of 2.01 to 3.04 t/ha and hybrid P64GE133 with a yield in the range of 1.96-3.02 t/ha. The hybrid DSL 403 had an average level of plasticity, its yield was 1.88-2.77 t/ha. A low level of plasticity was recorded in the 8X477KL hybrid with a yield of 1.71-2.82 t/ha and the Hector hybrid with a yield of 1.65-2.16 t/ha. The water consumption of sunflower hybrids for the formation of a yield unit (t/ha) was calculated for each year of the study: the dry year – 927 ± 80 m^3/ha, the average humid year – 1106 ± 163 m^3/ha, the wet year – 1540 ± 232 m^3/ha. A yield prediction function model was developed for each hybrid. Functions with a high level of approximation describe the spatiotemporal processes of yield vegetative formation for individual sunflower hybrids according to the level of moisture supply of the year. The function models were based on the raster models of the spatial distribution of *NDVI* values in the most active periods of intensive growth, flowering and seeding. For situational forecasting of the yield of sunflower hybrids, it is recommended to use a system of function models developed for different conditions of the crop's moisture supply and mineral nutrition. The proposed functions provide the 97.2-99.9% level of data approximation, which confirms the high accuracy of predicting the yield of sunflower hybrids. The research results are a relative for improving the methodology of vegetation research of agricultural crops, validating crop rotation, determining the effectiveness of agrotechnical measures, correct selection of varietal and hybrid composition, forecasting the yield of sunflower hybrids in the soil and climatic conditions of the Steppe zone.

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CONFLICT OF INTEREST

None.

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Просторово-часові закономірності та прогнозування вегетації гібридів соняшника в ґрунтово-кліматичних умовах зони Степу України

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Анотація. Довгострокові дослідження обробітку ґрунту та управління сільськогосподарськими культурами є важливими для визначення практик виробництва сільськогосподарських культур, які сприяють забезпеченню сталої врожайності та прибутку. Зокрема, в умовах зміни клімату актуальним питанням залишається вибір, прогнозування та коригування систем вирощування сільськогосподарських культур в зоні дефіциту вологи та ведення ризикового землеробства. Тому метою дослідження було встановлення просторово-часових закономірностей вегетаційного розвитку гібридів соняшнику та прогнозування їх продуктивності в ґрунтово-кліматичних умовах зони Степу України. Проведено детальний аналіз сезонних змін значень нормалізованого диференційного вегетаційного індексу у посівах гібридів соняшнику за період 2019-2021 рр. із використанням космічних знімків супутникового апарату Sentinel 2, оброблених із застосуванням ліцензійного програмного продукту ArcGis 10.6. Доведено достовірність результатів дослідження стану посівів у різні фази вегетації рослин на основі *NDVI* та можливість їх використання для прогнозування врожайності сільськогосподарських культур. Визначено пластичність різних гібридів соняшнику до ґрунтово-кліматичних умов зони Степу, зокрема гібридів Оплот, Гектор, ДСЛ403, П64ГЕ133, 8Х477КЛ. Розроблено модель функції прогнозування врожайності для кожного гібрида соняшника відповідно до рівня вологозабезпечення року. Достовірність моделей прогнозування склала 97,2-99,9 %. Рекомендовано використання системи моделей функцій, розроблених для різних умов вологозабезпечення та підживлення з метою ситуаційного прогнозування врожайності гібридів соняшника. Отримані результати досліджень можуть бути використані для удосконалення методики дослідження вегетації сільськогосподарських культур, обґрунтування сівозміни, вибору кращих практик застосування багатофункціональних ріст регулюючих препаратів, вставлення кліматичної пластичності сортів та гібридів, управління ресурсами, розробки адаптивно-кліматичних технологій у землеробстві та рослинництві, розрахунку їх ефективності, прогнозування урожайності та забезпечення прибутковості агровиробництва у зоні дефіциту вологи та ведення ризикового землеробства

Ключові слова: рослинництво; клімат; дистанційне зондування; супутникові знімки; моделювання