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Application of the Research on Spatio-Temporal Differentiation of a Vegetation Index in Evaluating Sunflower Hybrid Plasticity and Growth-Regulators in the Steppe Zone of Ukraine

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ABSTRACT
The purpose of the study was to establish dependence of sunflower productivity on hybrid plasticity under the climatic conditions of the Steppe zone and effectiveness of growth-regulators on the basis of the analysis of differentiation of a vegetation index. The research on the development and productivity of different sunflower hybrids under the natural-climatic conditions of the Steppe zone of Ukraine was conducted in the years of 2019 (medium-wet), 2020 (dry) and 2021 (wet). Spatio-temporal differentiation of the vegetation of sunflower hybrids was established on the basis of calculation of a normalized difference vegetation index (NDVI) using the data of the decoded space images of Sentinel 2. Cartographic and grapho-analytical materials reflecting the reaction of plants to natural-climatic conditions and multifunctional growth-regulators were obtained. The dependence of the reaction of sunflower hybrids to multifunctional growth-regulators on their plasticity in response to the natural-climatic conditions of the Steppe zone was established. There was a weak reaction to application of growth-regulators of the sunflower hybrids Oplot and P64HE133 which are characterized by a high level of plasticity in response to the natural-climatic conditions of the Steppe zone. It was proven that the application of the biological preparation Helafit Combi exceeded the level of agrocenoses productivity in comparison with the chemical preparation Architect™ by 1.1-5.4%. It was established that foliar treatment with growth-regulators led to a decline in water uptake by the sunflower hybrids by 1.2–10.0% in the dry year, by 3.8–8.6% in the medium-wet year and by 3.7%–21.9% in the wet year. There was a significant reduction in the level of water uptake by the hybrid Hector – by 7.7–10.0% and the hybrid 8KH477KL – by 1.2–21.9%.The research results are the basis for forecasting the development of sunflower hybrid crops with further measurement of the crop productivity that allows establishing a probable level of efficiency of sunflower hybrid production by agricultural producers under the climatic conditions of the Steppe zone.

Keywords: sunflower, growth-regulatory preparations, climate, vegetation, NDVI, Steppe zone, remote sensing.

INTRODUCTION

Climate change is a global environmental problem of humanity. It is difficult to solve it because of the global issue of food security requiring intensification of agricultural research in the direction of production adaptation to climate changes. Climate changes are characterized by diversity, different levels of intensity of their manifestations, frequency of climate anomalies, periodicity of extreme weather events in space and time (Lisetskii et al. 2016; Dudiak et al. 2019; Wang et al. 2019; Dikshit et al. 2021; Pichura et al. 2022). An increase in the frequency and intensity of extreme weather events and intensification of land use cause disruption in the functioning of natural and artificial ecosystems (Lisetskii et al. 2019; Zhang et al. 2019; Oti et al. 2020; Pichura et al. 2019, 2020, 2023) and accelerate environmental degradation (Assan et al., 2020; Breus et al., 2019, 2020; Dudiak et al. 2019, 2020, 2021, Özşahin 2023; Xie et al. 2023).

Physical-geographical Steppe zone is characterized by a high level of temperature regime, scarce, unstable and uneven distribution of precipitation that determine risky agricultural conditions and insufficient yields of agricultural crops (Loison et al., 2017; Pichura et al., 2021; Mateo-Sanchis et al., 2021). Over the past 20 years, there has been an increase in the frequency of anomalous climate manifestations by three times, causing a rise in the average annual temperature by 2.6 °C and an increase in the frequency of downpours in spring and summer (Pichura et al., 2022). The consequence of these phenomena are a decrease in rainfall productivity, more intensive soil erosion processes and a higher level of risks of washing out agricultural crops from the fields, disruption of transpiration processes and increased evaporation of moisture in summer and autumn, as well as worse moisture supply of agrocenoses. Under such extreme climatic conditions, moisture is a limiting factor of agricultural crop productivity (Peter Török et al., 2020; Kotova et al., 2010), therefore, important tasks in agriculture include agro-technological conservation of pre-planting soil moisture and efficient use of moisture content during the growing season (Domaratskiy et al., 2018, 2020, 2022).

Application of remote sensing data for examining crop growing conditions on the basis of a normalized difference vegetation index (NDVI) is an encouraging trend in agricultural science (Essaadia et al., 2022; Ding et al., 2022; Beyer et al., 2023). Spatio-temporal differentiation of a vegetation index of agrocenoses is an indicator of the state of plant development at different phenological stages depending on natural-climatic conditions, volumes and character of rainfall, the level of agro-technological measures. It allows determining the level of hybrid plasticity in response to natural-climatic conditions of certain physical-geographical zones and evaluating agricultural crop productivity. In order to forecast crop yields, it is necessary to perform a thorough analysis of seasonal changes of vegetation index values to verify the curves of plant growth by different scenarios of cultivation, prior field research and actual yield records of certain varieties and hybrids.

Researchers prove (Anfang et al., 2021) that plant growth and reaction to the environment is determined by their hormones affecting the processes of biosynthesis, metabolism and the level of perception of external impact factors by acrocenoses. However, abnormal manifestations of climate change cause stress with a further decrease in the level of hormones (Bhattacharya, 2019; Kondhare et al., 2021), which is a reason for plant weakness, stunting, weaker immune system and slower growth, an increase in their susceptibility to diseases and pests. In order to reduce the impact of stress factors on a plant organism, growth-regulators containing phyto-hormones and other synthetics growth-stimulators are applied. Their effect is directed towards prolongation of active photosynthesis, cessation of leaf apparatus activity and intensification of growth functions (Small et al., 2018; Mu et al., 2018; Panfilova et al., 2019, 2021).

The state of agrocenoses cover, activeness of photosynthetic processes, production of chlorophyll content at different phenological stages can be modeled through identifying the spectral reflectance characteristics of plants on satellite images that is a necessary stage of research on variety and hybrid plasticity in response to natural-climatic conditions. This, in turn, allows improving technologies of agricultural crop production through correcting agro-technological measures, optimizing planting timelines and applying growth-regulators.

Sunflower is a major oil-bearing crop in Ukraine, its share in the structure of crop rotations makes 25-28%. Seeds of modern released varieties and hybrids contain 50–52% of oil, and those of selected varieties and hybrids – up to 60%; therefore, they require a high level of moisture content (Koutroubas et al., 2020; Domaratskiy 2021; Jan et al., 2022). The level of water uptake in sunflower changes during the growing season: plants consume about 20% of moisture from germination to capitulum formation; consumption of total moisture equals 60% at the phenological stages of capitulum formation and flowering. Sunflower is characterized by the ability to absorb moisture from a soil layer up to 3.0 meters deep and desiccate a soil layer up to 1.5 m deep.

Studies established (Howell et al., 2015; Domaratskiy et al., 2020–2022; Giannini et al., 2022) that sunflower productivity did not exceed 50% of its biological potential when standard agro-technological measures were taken in the zones of rain-fed agriculture. An increase in agricultural crop productivity is possible due to application of multifunctional growth-regulators of a combined effect in the zones of extreme agriculture. Such preparations have a stimulating and antifungal effect, increasing plant resistance to pathogenic microflora.

The purpose of the research was to establish the dependence of sunflower productivity on hybrid plasticity in response to climatic conditions of the Steppe zone and effectiveness of growth-regulators on the basis of the analysis of differentiation of a vegetation index.

MATERIAL AND METHODS

The research on development and productivity of different sunflower hybrids under natural-climatic conditions of the Steppe zone of Ukraine was conducted in 2019–2021 in the research field of Mykolaiv State Agricultural Research Station of the Institute of Irrigated Agriculture of the National Academy of Agricultural Sciences (the SARS IIA of the NAAS) of Ukraine (Fig. 1). The experiments were carried out without irrigation. The total area of the experiments was: in 2019 – 1.9 ha, in 2020 – 8.4 ha and in 2021 – 0.75 ha.

Program of scientific research

A two-factor field experiment was designed: Factor A – sunflower hybrid with high oil content

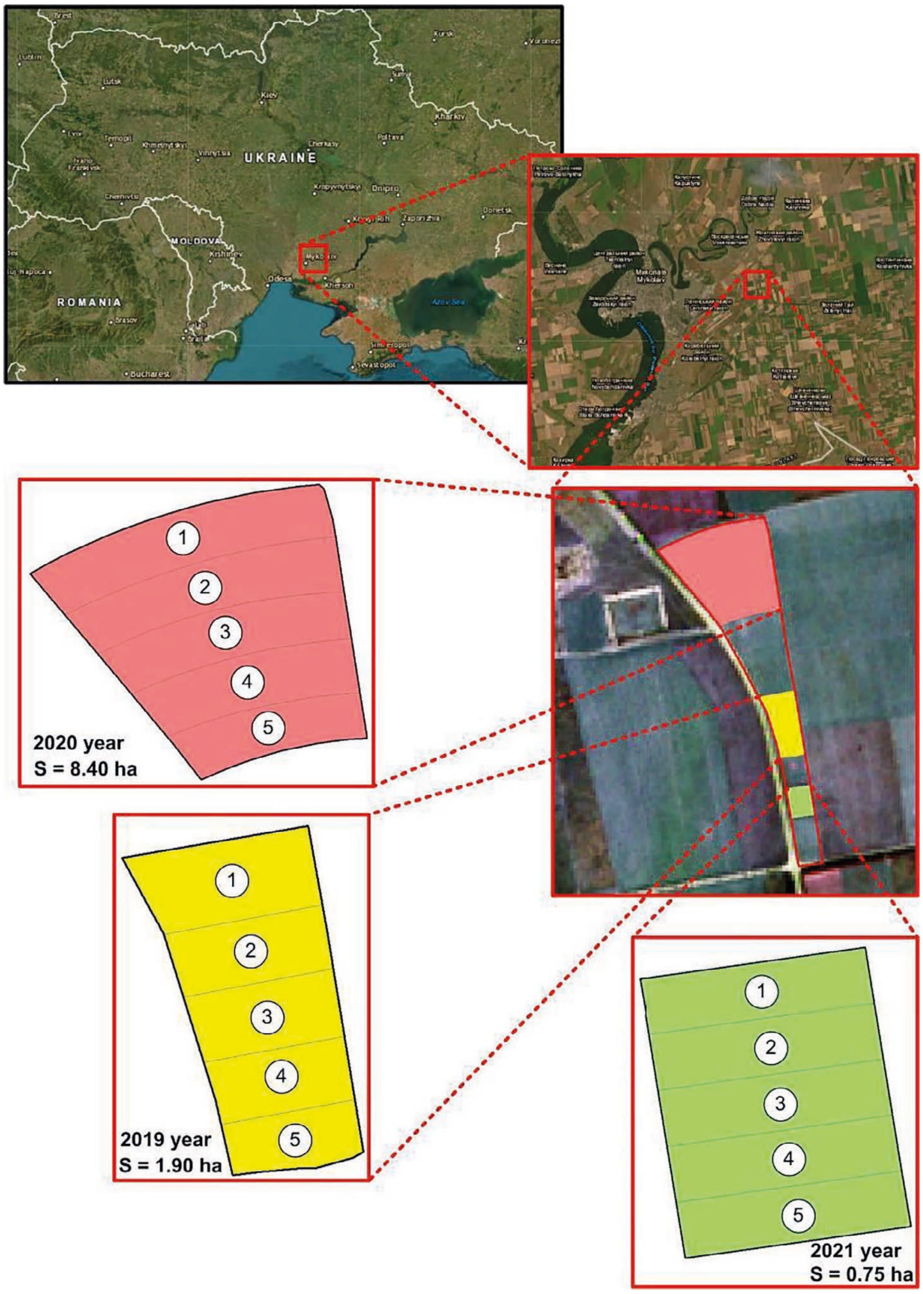


Figure 1. Location of the research fields and placement of sunflower hybrid crops in 2019–2021: 1 – Oplot; 2 – Hector; 3 – DSL403; 4 – P64HE133; 5 – 8KH477KL

of Ukrainian and foreign breeding, Factor B – foliar treatment of plants with multifunctional growth-regulators with antifungal properties.

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

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

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

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

Methods for analysis and calculation of climatic parameters

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

The value of the balance of solar radiation (*R*, Kcal/cm^2) and energy expenditures of climate for soil formation (*Q*, MJ/m^2) are important derivative parameters of the characteristics of climate changes and evaluation of their impact on the development and productivity of agricultural crops.

The balance of solar radiation (*R*, kcal/cm^2) was calculated by the formula (Lisetskii et al., 2014; Dudiak et al., 2019):

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

where: *T* – the value of the average air temperature during the growing season, °C.

The method of bioenergetics research was applied to calculate the values of energy expenditures of climate for soil formation, since it allows modelling scenarios of climate impacts given in energy equivalents by the formula (Volobue, 1974, Rasmussen, 2007; Lisetskii et al., 2014; Pichura et al., 2021):

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

where: *R* – the balance of solar radiation, kcal/cm^2; *P* – the total precipitation in the growing season, mm.

Methods for decoding space imagery and spatial analysis

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

The value of NDVI was calculated by the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (3)$$

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

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

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

In order to improve the quality of map visualization of spatio-temporal distribution of the values of NDVI and increase the reliability of interpretation of a vegetation index within certain areas and characteristics of vegetation heterogeneity of sunflower hybrid crops, the values obtained on the basis of decoding the space imagery of Sentinel 2 were interpolated. Interpolation was performed using the method of geostatic analysis of a radial basis function (Kamińska et al., 2014; Pichura et al., 2023). This deterministic method allows establishing accurate interpolated surface of a change in the values of NDVI and storing the initial raster data. Histogram and semivariogram methods were used as an additional graphical analytical instrument for evaluating spatio-temporal changes in the values of NDVI. The histograms allowed examining a change in the frequency and density of vegetation index values in terms of each phenological stage of sunflower hybrids under different conditions of climate formation. The semivariogram allowed visualizing spatial heterogeneity of the vegetation index values.

Space images were processed, maps were created and spatio-temporal analysis was performed using the licensed ArcGis 10.6 software.

RESULTS AND DISCUSSION

Soil properties of the research plots

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

Analysis of the climatic conditions of the research

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

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

There has been an increase in the frequency of abnormal manifestations of heavy rainfalls over the past 10–15 years. In July, 2020 (Fig. 3) there was an extreme increase in the vegetation index during the period of sunflower flowering (BBCH 61–69), but heavy rainfalls did not have positive energy and a long-term effect on the formation of sunflower hybrid productivity. In particular, in a dry year (2020) a high level of the standard deviation (84.1 mm) and a high level of variance of seasonal changes in precipitation (139.7%) were registered, which confirms their abnormal manifestations in the growing season.

It is necessary to highlight that the average monthly value of the norm of precipitation in the growing season for 50 years (1970–2020) was 43.6 mm, the standard deviation was 12.6 mm, and the level of variance equaled 28.9%. The year of 2019 was close to the typical climatic conditions (the norm): the average monthly value of

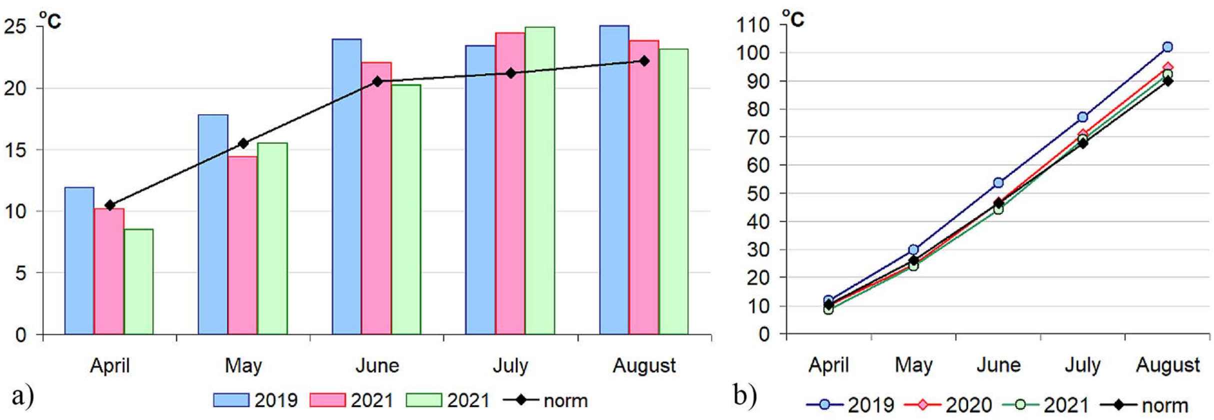


Figure 2. The average monthly air temperature (°C) in the growing season of sunflower crops in 2019–2021: (a) dynamics of temperature; (b) curves of accumulated average month temperatures

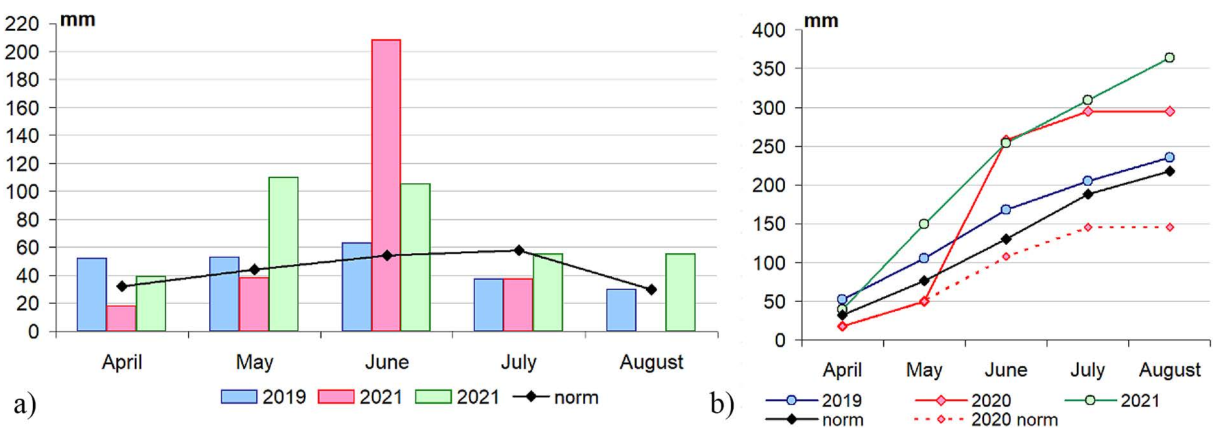


Figure 3. The amount of precipitation (mm) in the growing season of sunflower crops, 2019–2021: (a) dynamics of precipitation; (b) curves of accumulated precipitation

precipitation in the growing season was 47.0 mm, the standard deviation was 13.3 mm, the level of variance equaled 28.3%. The year of 202, a typical wet year for the Steppe zone, was characterized by the average monthly value of precipitation of 72.8 mm, the standard deviation of 32.4 mm and an increased level of variance – 44.5%.

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

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

In order to forecast sunflower hybrid yields, it is necessary to measure bio-climatic potential of the area under crops, which is calculated on the basis of the balance of solar radiation (*R*, MJ/m^2) and precipitation (*P*, mm), determining the total energy of climate expenditures for soil formation (*Q*, MJ/m^2). According to the calculations, the total value of the energy norm of climate expenditures in the growing season equals 418.8 MJ/m^2, in the year of 2019, which is close to the typical climatic conditions; in turn, the value *Q* equaled 466.8 MJ/m^2, while in the wet year of 2021 – 940.4 MJ/m^2. In 2020, the abnormal value of precipitation in July was adjusted to typical conditions of a dry year with the total precipitation of 145 mm in the growing season (Fig. 3b, the curve – 2020 norm); further, it was found that the total value of energy of the climate expenditure was at the level of 145.2 MJ/m^2. Scientists proved that the main limiting factor of the formation of crop yield is productive moisture determining the volume of absorption of soil macro- and micro-elements necessary for plant growth and development. In a dry year, a drop in productive moisture leads to a reduction in energy of climate expenditure and bio-climatic potential of the territory, determining a decline in the volume of absorption of macro- and micro-elements necessary form plant growth and development that decreases the level of energy of plant development.

Examination of the state of sunflower hybrid crops

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

The index value of NDVI in the research fields, in 2019, 2020 and 2021, was calculated on the basis of the data of satellite images of the space vehicle Sentinel 2. Using the images, the state of plant herbage, absorbing electromagnetic waves in a visible red band and reflecting them in a near infra-red band, was identified. In particular, (the central length of the wave of Sentinel 2 is 665 nm) maximum absorption of solar radiation by chlorophyll falls on a red spectrum zone, and maximum reflection of energy by a leaf cell structure falls on a near infrared zone (the central length of the wave of Sentinel 2 is 842 nm). In other words, high photosynthetic activity is reflected in a low value of the coefficients of reflection in a red spectrum zone and a high value in a near infrared zone. The relationship of these indices allows distinguishing vegetation from other natural objects and also calculating the value of NDVI within 0–1.0. After decoding the images, the spectral analysis of distribution of the values of NDVI was performed and the spatio-temporal heterogeneity of the development of sunflower hybrid crops was established. The advantages of using NDVI are moderate sensitivity to changes in soil and atmospheric backgrounds and a high level of identification of plant photosynthetic activeness.

A medium-met year (2019)

As a result of decoding the series of satellite images in a medium-wet year (2019 p.), at the beginning of the growing season (May, 5, 12 days after the sowing date), simultaneous germination (Fig. 4) in the sunflower hybrid crops with the average index value of NDVI – 0.26±0.03 and an insignificant level of spatial variance – 8.1%, were identified.

Homogeneity of sprouts is confirmed by the density of the values of NDVI on the bar graph (Fig. 5) and their insignificant dispersion on the graph of semivariogram. After foliar treatment of sunflower hybrids, there was heterogeneous reaction of the plants to multifunctional growth-regulators, which was registered on the satellite image on May, 30 (37 days after the sowing date). It is necessary to emphasize a positive reaction and intensification of the development of the crop hybrid Oplot, the value of NDVI ranged from 0.54 to 0.77, the hybrid Hector with the values of NDVI within 0.54–0.80 and the hybrid DSL403 with the values of NDVI – 0.51–0.78. There was a weak reaction to growth-regulators in the hybrid P64HE133 with the value of NDVI – 0.41–0.67 and the hybrid 8KH477KL with the value of NDVI – 0.43–0.62. At the end of the phenological stage "capitulum formation", on June, 14 (52 days after the sowing date) and the beginning of the stage "flowering", on June, 19 (57 days after the sowing date), a good (0.55–0.7) and very good state of the vegetation of all the sunflower hybrids (> 0.7) was registered. In this period, the average value of NDVI equaled 0.72±0.06; the level of spatial heterogeneity was 8.2%. Homogeneity of plant vegetation is an evidence of

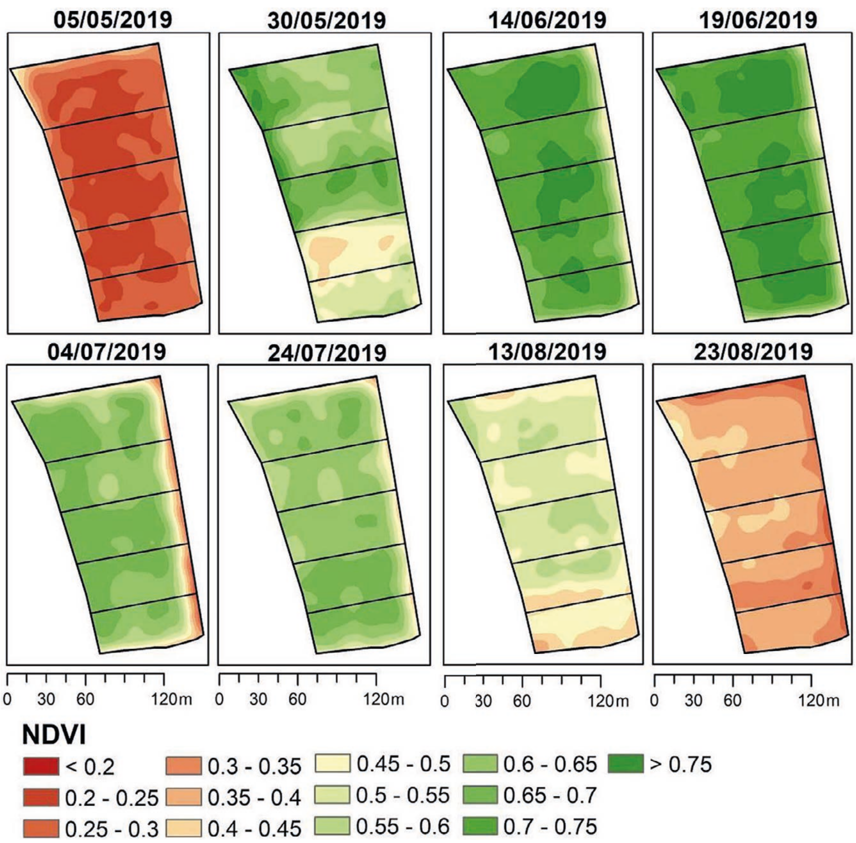


Figure 4. Seasonal distribution of NDVI of the sunflower hybrids in the research field (2019)

a complex effect of productive precipitation and multifunctional plant growth-regulators.

The second half of the growing season of the sunflower hybrids in 2019 includes the second half of the flowering stage (BBCH 67-69) and the macro-stages “fruiting” (BBCH 71–79), “fruit and seed maturation” (BBCH 80–89) and “dying” (BBCH 92-99), which are components

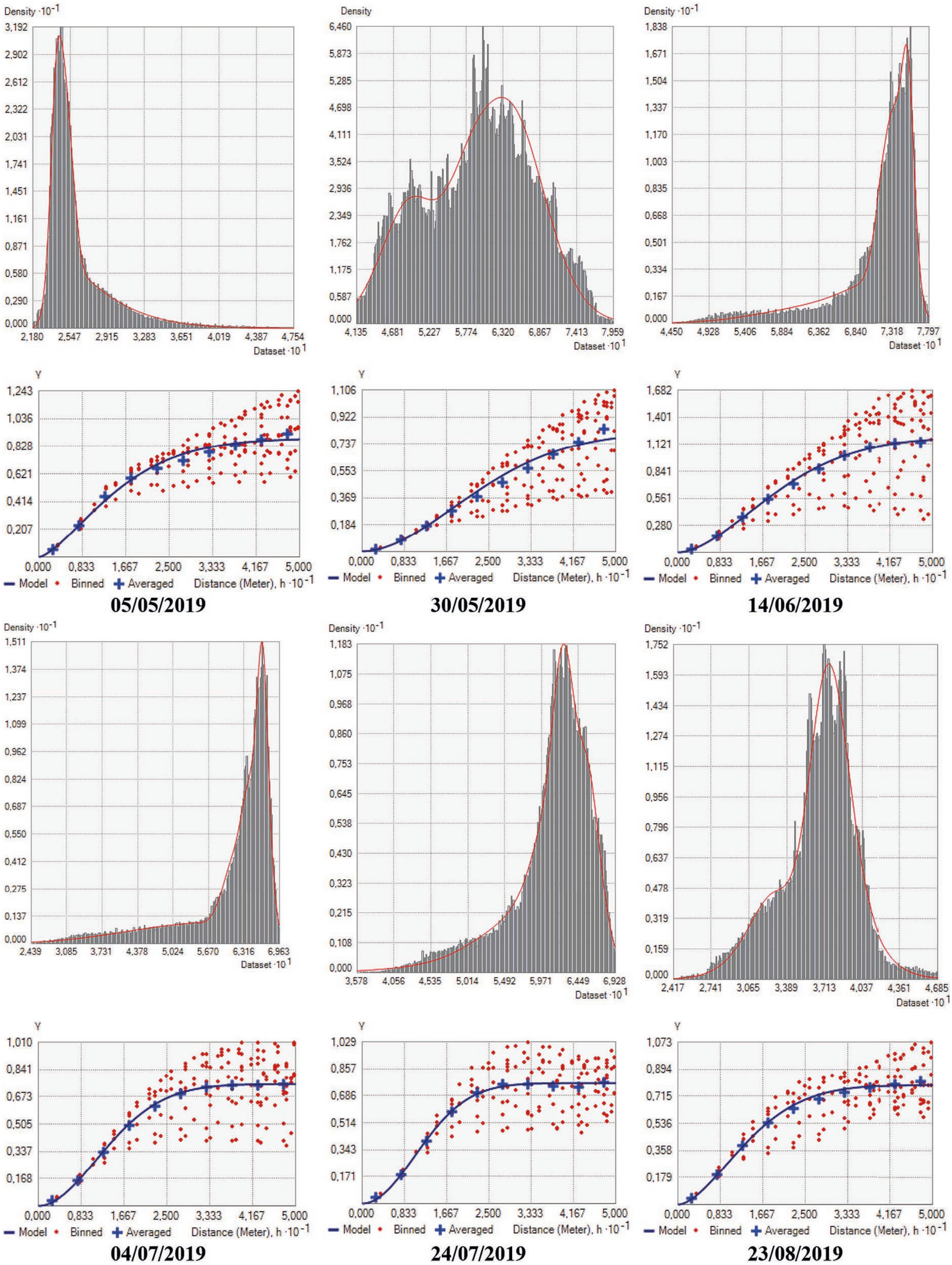


Figure 5. Histograms and semivariogram of seasonal distribution of NDVI of the sunflower hybrids in the research field (2019)

of the phenological stage of maturation (BBCH 71–99). It is necessary to highlight that the second half of the growing season was characterized by stressful conditions, determined by water deficiency and an increased air temperature. It caused a sharp deterioration in photosynthetic processes and shorter duration of the macro-stage "fruiting". On July, 4th (72 days after the sowing date), a medium value of NDVI – 0.63±0.09 with visible signs of heterogeneity of the formation of the sunflower hybrid productivity was registered, the level of spatial variance being 14.1% (Fig. 5).

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

A dry year (2020)

In 2020, there were extremely dry conditions for growing sunflower hybrids, which caused a reduction in the growing season and dates of certain phenological stages of plants. In particular, the beginning of the growing season in 2020 was characterized by a low level of soil moisture content and a small amount of precipitation. It determined poor germination and a critically low level of photosynthetic processes at the beginning of the phenological stage of capitulum formation (Fig. 6).

After treating the crops during the period of the formation of 6–8 true leaves, there were slow reactions of all the hybrids to multifunctional growth-regulators, which were determined by stressful climatic conditions. The data of the decoded satellite image created on May, 19th (21 days after the sowing date) allowed calculating a low level of the value of NDVI – 0.23±0.02 (Fig. 6) with an insignificant level of variability – 8.2%. Homogeneity of sprouts is low, stressful growing conditions at the beginning of the stage of capitulum formation were registered on the histogram and the graph of semivariogram (Fig. 7).

Deficiency of precipitation caused further stunted plant growth that was confirmed by the results of the decoded satellite image created on June, 8th (41 days after the sowing date), the value of NDVI equaled 0.36±0.04 with a

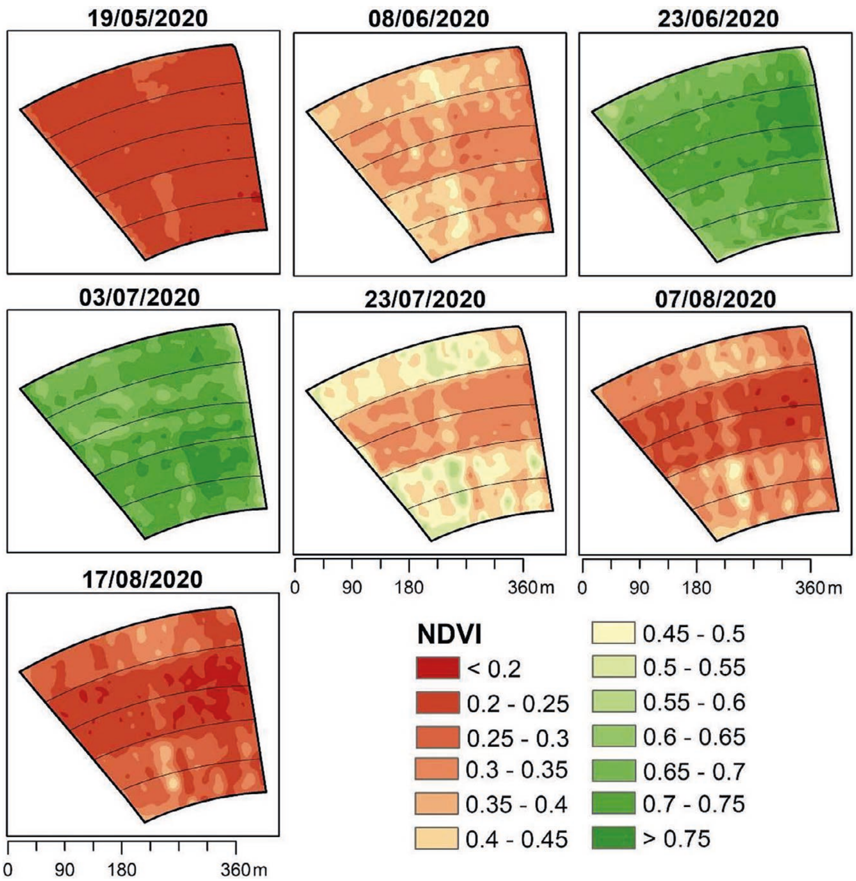


Figure 6. Seasonal distribution of NDVI of the sunflower hybrids in the research field (2020)

significant level of variance – 10.3%. June of 2020 was characterized by heavy rainfalls enhancing the effect of growth-regulators on photosynthetic processes in the sunflower hybrids. At the beginning of the flowering stage, on June, 23th (56 days after the sowing date), the value of NDVI equaled 0.70±0.03 with an insignificant level of variance – 4.9%.

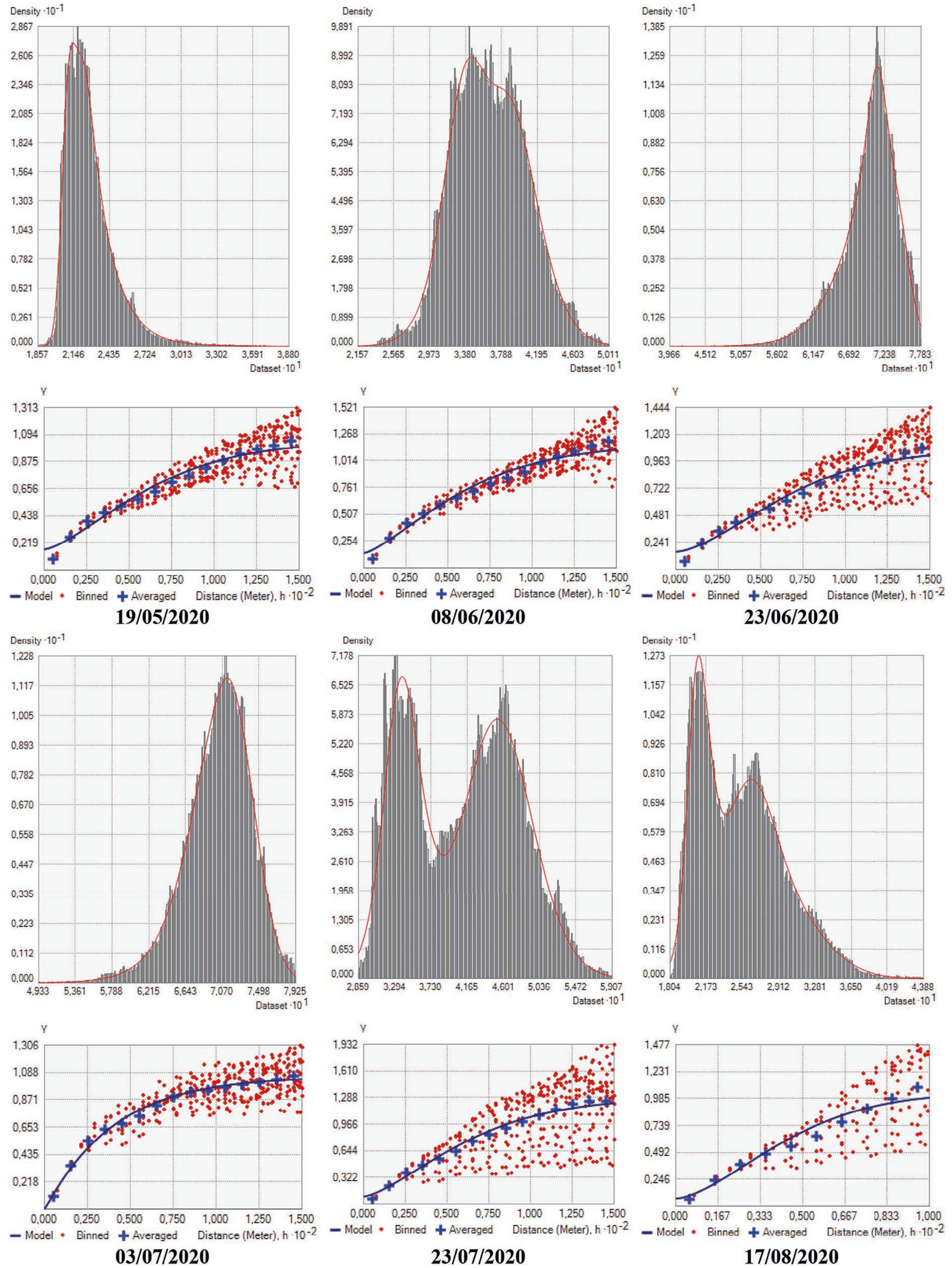


Figure 7. Histograms and semivariogram of seasonal distribution of NDVI of the sunflower hybrids in the research field (2020)

The end of the flowering stage, July, 3th (56 days after the sowing date), was also characterized by high values of NDVI – 0.69±0.03 with the level of variance – 9.8%. Deficiency of atmospheric and soil moisture in the second half of the plant growth caused a sharp decline in photosynthetic activeness of the sunflower hybrids and shorter duration of the macro-stage "fruiting" (BBCH 71–79), stimulated faster "fruit and seed maturation" (BBCH 80–89) and "dying" (BBCH 92-99), on July, 23rd (86 days after the sowing date) the value of NDVI equaled 0.41±0.04 with the level of variance – 9.8%. On August, 7th (101 days after the sowing date) the value of NDVI equaled 0.30±0.04 with a high level of variance – 12.2%.

At the plant macro-stage "dying", on August, 17–18 (112 days after the sowing date), the value of NDVI was 0.25±0.03 with a high level of spatial variance – 11.6%. A high level of spatial variance is determined by considerable spatial heterogeneity of plants because of stress caused by climatic conditions. It was established that the sunflower hybrids Hector and DSL403 matured faster in dry periods. The process of heterogeneous maturation of different hybrids is marked by peaks on the histogram (Fig. 7) and characterized by significant dispersion on the graph of semivariogram. Deficiency of moisture caused deterioration in photosynthetic processes, a significant decline in chlorophyll content in the plants, a shorter duration of important phenological stages and the growing season of the sunflower hybrids on the whole.

A wet year (2021)

The beginning of the growing season in 2021 was characterized by favorable climatic conditions in the pre-sowing period, which ensured a high level of moisture content in the soil in the sowing period. It determined high energy and uniform emergence of seedlings registered on May, 14th (5 days after the sowing date), the index value of NDVI was 0.25±0.03, the level of spatial variance equaled 6.2% (Fig. 8, 9).

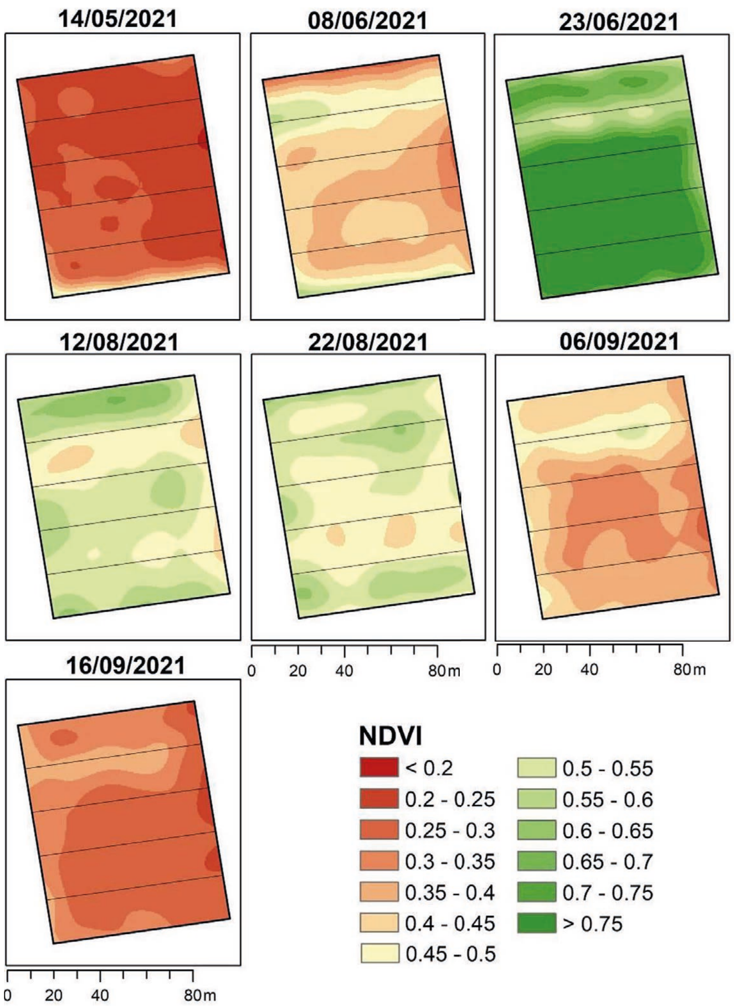


Figure 8. Seasonal distribution of NDVI of the sunflower hybrids in the research field (2021)

After the plant treatment, on June, 8th (21 days after the sowing date), there was high heterogeneity of the hybrid reaction to multifunctional growth-regulators (Fig. 8, 9), which was determined by redistribution of moisture in the field and the hybrid plasticity in response to the climatic conditions of the Steppe zone. The value of NDVI equaled 0.42±0.04 with a high level of spatial variance – 14.0%.

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

At the phenological flowering stage of the sunflower crops, all the hybrids were characterized by a high level of photosynthetic process, on June, 23rd (45 days after the sowing date) the value of NDVI equaled 0.75±0.06 with the level of spatial variance – 8.5%. Systematic productive precipitation and high moisture content in the soil in the first half of the growing season determined a longer phenological stage of flowering that contributed to an increase in the plant productivity. In 2021, the flowering stage lasted 33 days that was 2.3 times longer than in the previous years of 2019 and 2020. The maximum value of NDVI in the flowering period was 0.89-0.93. A high level of NDVI was registered at the phenological stage of "fruiting" – 0.74 (76 days after the sowing date) and the macro-stage "fruit and seed maturation" – 0.54 (95 days after the sowing date).

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

A summary of the results of the research on the state of the sunflower hybrid crops

The results of the decoded series of the satellite images of Sentinel 2 allowed establishing regularities of spatio-temporal photosynthetic processes of certain sunflower hybrids in the growing season (Fig. 10). The obtained cartographic and grapho-analytical materials reflect the plant reaction to natural-climatic conditions and multifunctional growth-regulators. The results of the cross-correlation research allowed establishing a high correlation of the seasonal distribution of NDVI of the sunflower hybrids – 0.92–0.99 that made it possible to accomplish objective verification of the vegetation curves by three natural-climatic scenarios of growing sunflower hybrids in the Steppe zone (Fig. 11). Over the years of the research, in the sowing period, the beginning of the growing season was characterized by the value of NDVI in open soil – 0.15. In the dry year of 2020, the growing season of sunflower crops lasted 116 days (Fig. 11a), in the medium-wet (Fig. 11b) and wet (Fig. 11c) years – 125 days.

Climate change determines the intensity of photosynthetic processes, production pf chlorophyll content and duration of phenological stages. In particular, in the dry year (Fig. 11a) there is a reduction in the duration of the flowering stage of the sunflower hybrids and a low level of the vegetation index of NDVI at the stages of capitulum formation and (0.22–0.40) maturation (0.30–0.40) that is related to a lack of productive precipitation and a high air temperature. In the first half of the growing season (BBCH 00–65) of the medium-wet year (Fig. 11b), there were favorable conditions for the plant development enhancing the effect of application of multifunctional growth-regulators. There was an increase in the value of NDVI from the sowing date (0.15) to the flowering stage (0.71) by a linear trend of a mathematical function – $NDVI = 0.0114t + 0.1371$ ($r^2 = 0.99$). The second half of the growing season was characterized by a lack of precipitation that led to a reduction in moisture content in the soil causing shorter duration of the flowering stage. At the same time, application of growth-regulators and a relatively moderate air temperature contributed to longer duration of the macro-stage "fruiting" (BBCH 71–79) and "fruit and seed maturation" (BBCH 80-89). In the wet year (Fig. 11c) (D, days) a phenological stage (F, a stage order) from the 1st to the 5th stage is presented by the function: $D = 4.849e^{0.4749F}$ ($r^2 = 0.99$).

The year of 2021 (wet) is characterized by longer duration of the flowering stage – by 2.3 times in comparison with the dry and medium-wet years, a high value of the vegetation index in the period

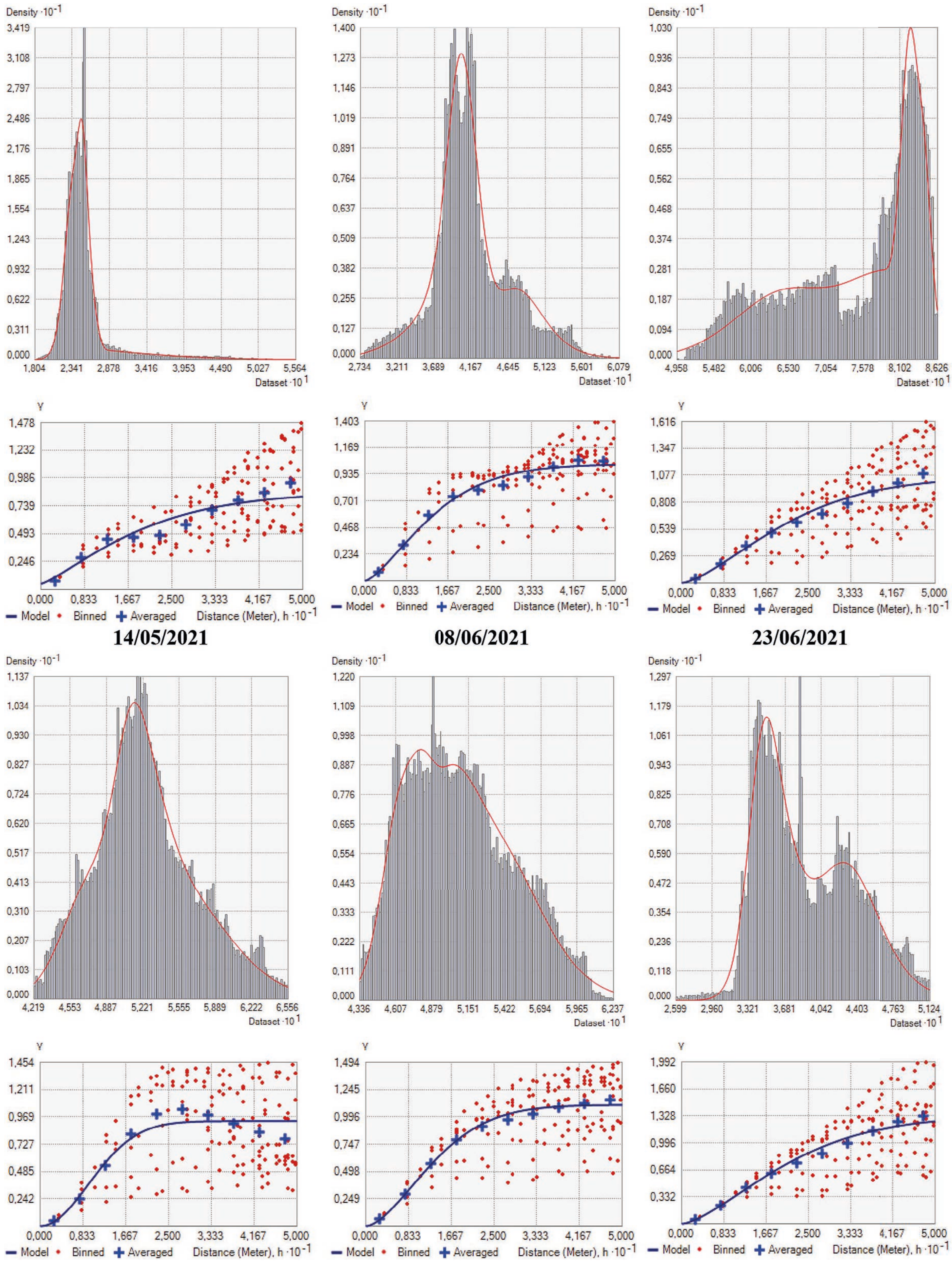


Figure 9. Histograms and semivariogram of seasonal distribution of NDVI of the sunflower hybrids in the research filed (2021)

of each phenological stage of plant development, a productive reaction to multifunctional growth-regulators. The research findings can be used for forecasting sunflower hybrid productivity.

Analysis of the sunflower hybrid productivity

The results of the experimental field research and analysis of the change in the state of sunflower hybrid crops under different climatic

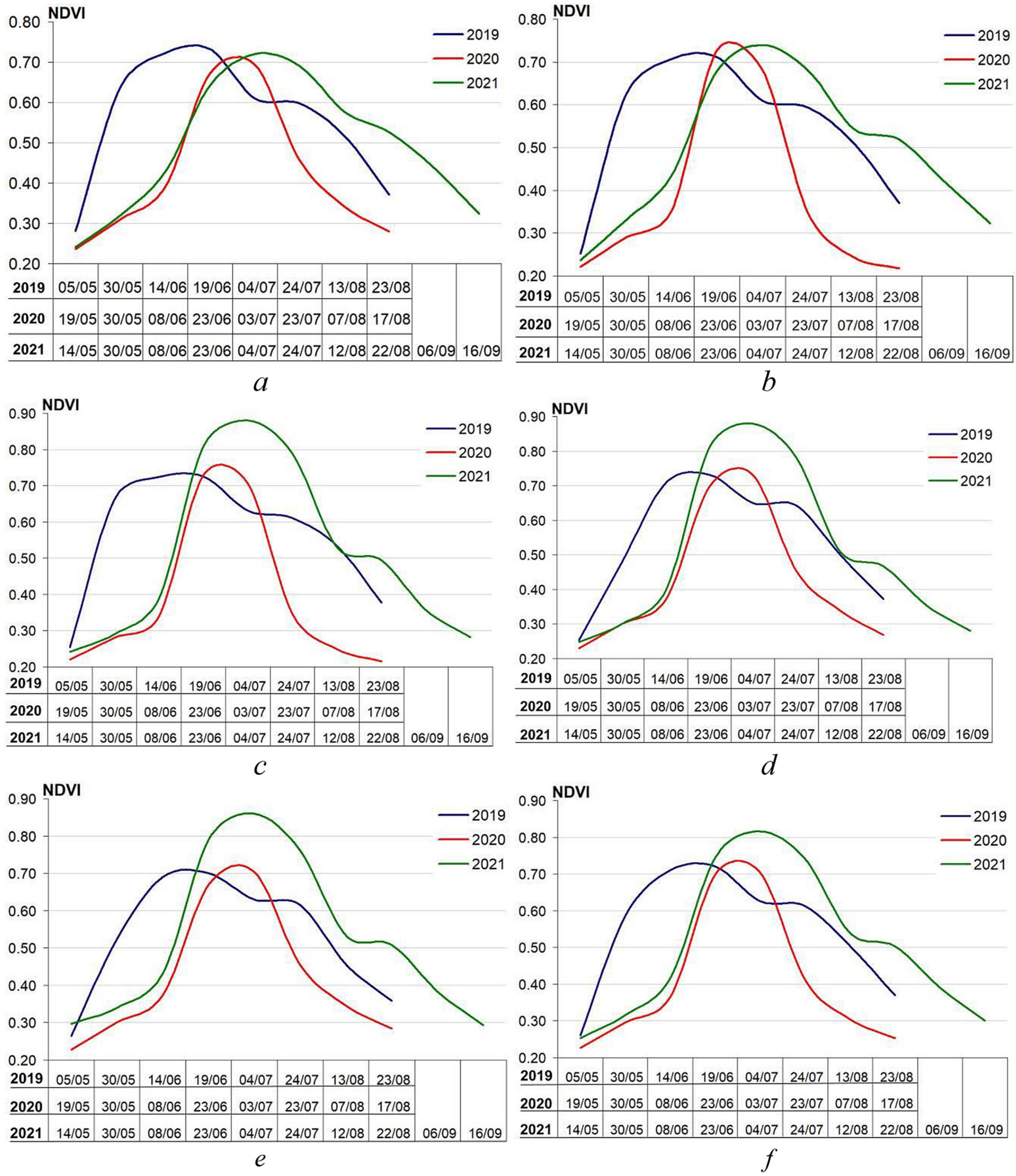
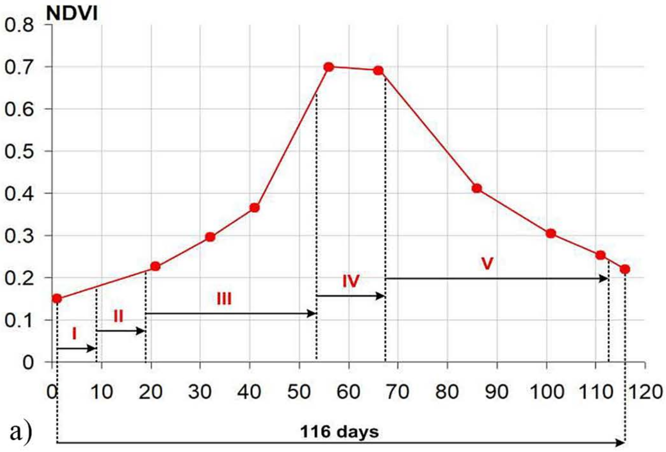


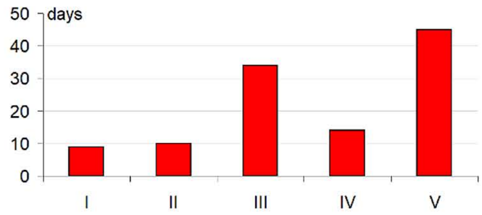
Figure 10. Seasonal distribution of NDVI of the sunflower hybrids in the research fields in 2019–2021: (a) Oplot; (b) Hector; (c) DSL403; (d) P64HE133; (e) 8KH477KL; (f) the annual average

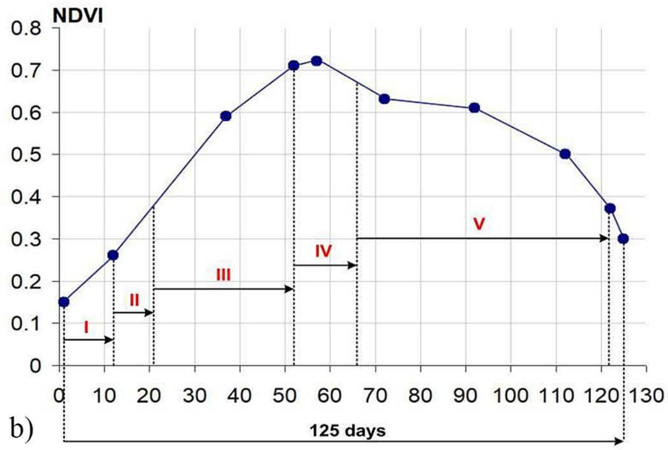
conditions allowed establishing effectiveness of application of multifunctional growth-regulators for improving the plant growing conditions aimed at increasing the sunflower hybrid productivity (Table 1).

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

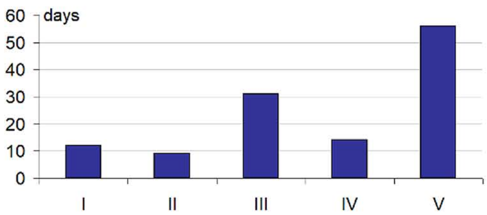


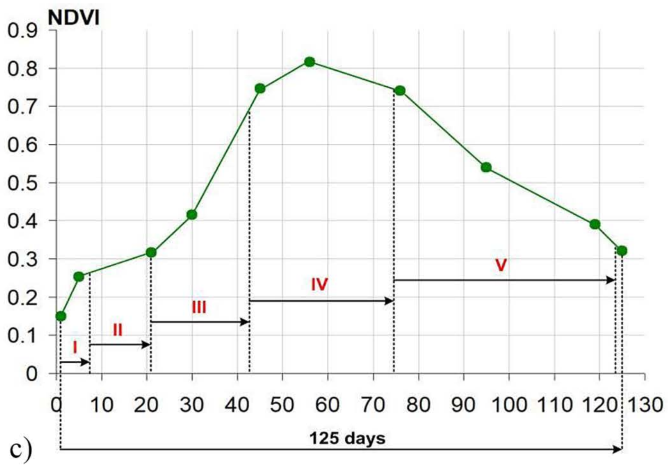
Stage	Days	NDVI
I	9	0.15→0.18
II	10	0.18→0.21
III	34	0.21→0.64
IV	14	0.64→0.70→0.68
V	45	0.68→0.24
Harvesting		0.22





Stage	Days	NDVI
I	12	0.15→0.26
II	9	0.26→0.38
III	31	0.38→0.71
IV	14	0.71→0.72→0.67
V	56	0.67→0.37
Harvesting		0.30





Stage	Days	NDVI
I	7	0.15→0.26
II	14	0.26→0.32
III	21	0.32→0.69
IV	33	0.69→0.82→0.75
V	49	0.75→0.34
Harvesting		0.32

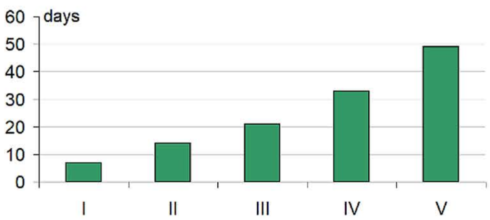


Figure 11. A seasonal change in NDVI at different phenological stages of sunflower hybrid development: (a) a dry year (2020); (b) a medium-dry year (2019); (c) a wet year (2021). Stage I – sprouting; Stage II – the first pair of true leaves; Stage III – capitulum formation; stage IV – flowering; stage V – maturation

18.1–34.5%, and there was an increase in their productivity by 0.3–30.4% in the wet year.

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

Analysis of the reaction of different sunflower hybrids to multifunctional growth-regulators allowed finding (Fig. 12) that the chemical preparation

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

Hybrids (Factor A)	Preparation (Factor B)	Years			Average for 3 years
		2019	2020	2021	
Oplot	Without preparations (control)	2.82	1.98	2.88	2.56
	Architect™	3.07	2.01	3.12	2.73
	Helafit Combi	3.10	2.04	3.11	2.75
Hector	Without preparations (control)	1.92	1.54	2.04	1.83
	Architect™	2.14	1.68	2.23	2.02
	Helafit Combi	2.10	1.72	2.22	2.01
DSL 403	Without preparations (control)	2.44	1.83	2.54	2.27
	Architect™	2.55	1.88	2.86	2.43
	Helafit Combi	2.60	1.93	2.90	2.48
P64HE133	Without preparations (control)	2.71	1.90	2.92	2.51
	Architect™	2.88	1.95	3.05	2.63
	Helafit Combi	2.89	2.02	3.10	2.67
8KH477KL	Without preparations (control)	2.22	1.68	2.41	2.10
	Architect™	2.37	1.71	2.96	2.35
	Helafit Combi	2.37	1.74	3.09	2.40
LSD05,t/ha	Factor A	0.09	0.07	0.09	-
	Factor B	0.12	0.11	0.10	-
	Interaction of Factors A and B	0.25	0.21	0.24	-

Architect™, in comparison with the control, led to an increase in productivity in the dry year – from 1.5% to 9.1%, in the medium-dry year – from 4.5 to 11.5%, in the wet year – from 4.5% to 22.8%. In particular, application of the biological preparation Helafit Combi led to an increase in the sunflower hybrid productivity in the dry year – from 3.0 to 11.7%, in the medium-wet year – from 6.6% to 9.9%, in the wet year – from 6.2% to 28.2%.

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

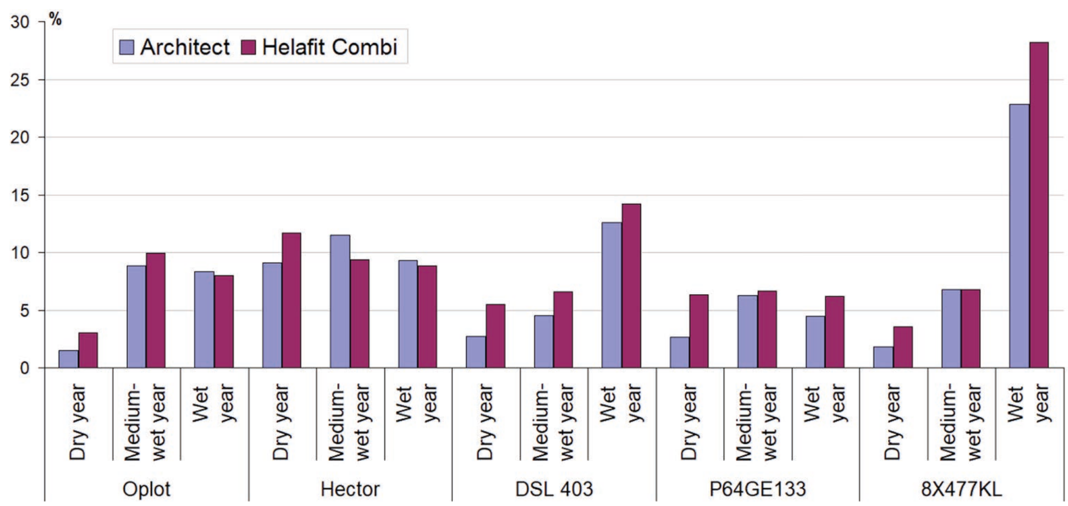


Figure 12. Effect of multifunctional growth-regulators on an increase in the productivity (%) of sunflower hybrids under conditions of the Steppe zone

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

It was established that the level of moisture uptake by sunflower is determined by its genetic features and the effect of multifunctional growth-regulators. The average value of water uptake in sunflower hybrids for the formation of a unit of productivity (t/ha) in the years of the research: the dry year – 927±80 m^3/ha, the medium-wet year – 1106±163 m^3/ha, the wet year – 1540±232 m^3/ha. The maximum level of water uptake for the formation of a unit of crop productivity (t/ha) was registered in the hybrid Hector: in the dry year – 1097 m^3/ha, in the medium-wet year – 1433 m^3/ha, in the wet year – 2038 m^3/ha; and also in the hybrid 8KH477KL: in the dry year – 1005 m^3/ha, in the medium-wet year – 1240 m^3/ha, in the wet year – 1726 m^3/ha. The minimum level of water uptake for the formation of a unit of crop productivity (t/ha) was registered in the hybrid Oplot: in the dry year – 853 m^3/ha, in the medium-wet year – 975 m^3/ha, in the wet year – 1444 m^3/ha, and also in the hybrid P64HE133: in the dry year – 889 m^3/ha, in the medium-wet year – 1015 m^3/ha, in the wet year – 1424 m^3/ha. It was established that the water uptake of sunflower hybrids is determined by their genetic features. A low level of water uptake by plants for the formation of a unit of crop productivity (t/ha) characterizes a high level of sunflower hybrid plasticity and resistance to extreme climatic conditions in the Steppe zone.

The effect of multifunctional growth-regulators on plant development is confirmed by an increase in crop productivity and a reduction in the level of water uptake for the formation of a unit of crop productivity (t/ha). It was established that foliar treatment with growth-regulators led to a reduction in water uptake by the sunflower hybrids (Fig. 13): the dry year – 1.2–10.0%, the medium-wet year – 3.8–8.6%, the wet year – 3.7%–21.9%. There was a significant decline in the level of water uptake by the hybrids Hector – from 7.7 to 10.0% and 8KH477KL – from1.2 to 21.9%.

An advantage of the biological growth-regulator Helafit Combi over the chemical preparation Architect™ was proven. In particular, application of the biological preparation Helafit Combi leads to a decline in water uptake by the sunflower hybrids by 5.1±2.9% in the dry year, by 6.8±1.4% in the medium-wet year and by 10.8±6.7% in the wet year. Application of the chemical preparation Architect™ reduced water uptake by the sunflower hybrids by 2.9±2.8% in the dry year, by 6.5±2.4% in the medium-wet year and by 9.4±5.4% in the wet year.

CONCLUSIONS

A spatio-temporal dependence of sunflower hybrid productivity on hybrid plasticity and

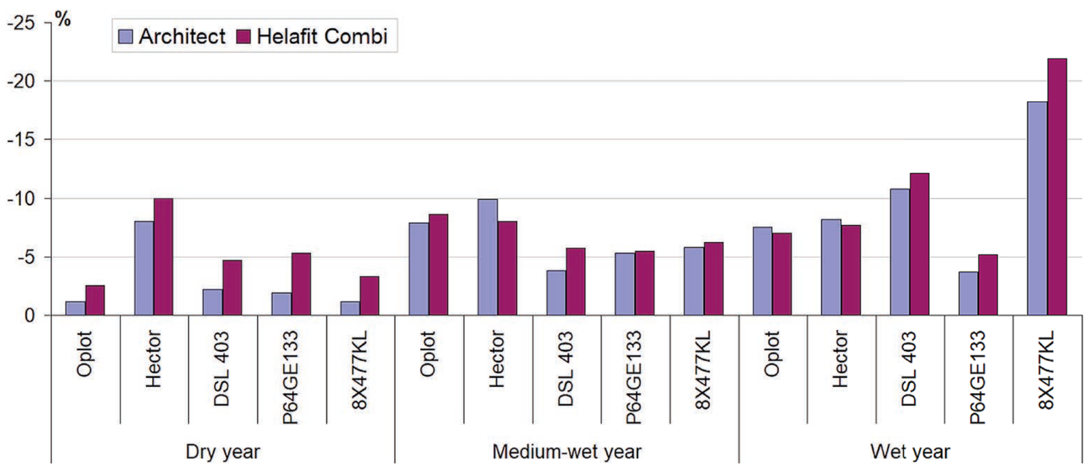


Figure 13. Share of a decline in water uptake in the sunflower hybrids depending on application of growth-regulators and natural moisture content

application of growth-regulators was found on the basis of analysis of differentiation of the vegetation index determined by means of the decoded satellite images of Sentinel 2 in the growing seasons of 2019, 2020 and 2021. It was established that climate change has a considerable impact on the intensity of photosynthetic processes, chlorophyll production and phenological stages of plants. It was proven that in the dry year (2020) there was shorter duration of the flowering stage of the sunflower hybrids. A low level of the vegetation index of NDVI at the stage of capitulum formation (0.22–0.40) and at the stage of maturation (0.30–0.40) was also registered. In the medium-wet year, in the first half of the growing season, there were favorable conditions for plant development and a positive reaction to application of multifunctional growth-regulators, and the second half of the growing season was characterized by a reduction in moisture content in the soil and shorter duration of the flowering stage of the sunflower hybrids. In the wet year, longer duration of the flowering stage, high values of the vegetation index at all the phenological stages of the plant development and a positive reaction to multifunctional growth-regulators were registered. The effectiveness of application of multifunctional growth-regulators was proven. Application of the preparations contributed to an increase in the productivity of the sunflower hybrids: in the dry year –1.5–11.7%, in the medium-wet year – 4.5–11.5%, in the wet year – 4.5–28.2%. There was a decline in water uptake by the plants in the dry year – within 1.2–10.0%, in the medium-wet year – 3.8–8.6%, in the wet year – 3.7–21.9%. Dependence of the reaction of the sunflower hybrids on the hybrid plasticity in response to the natural-climatic conditions of the Steppe zone and the effect of multifunctional growth-regulators was established. A high level of sensitivity of the hybrid Hector to growth-regulators in the dry and medium-wet years was identified, an increase in its productivity being 9.1–11.7%. In the wet year, application of the preparations led to a considerable increase in the productivity of the hybrid DSL403 – 12.6–14.2% and that of the hybrid 8KH477KL – 22.8–28.2%. A weak reaction to application of growth-regulators was registered in the sunflower hybrids Oplot and P64HE133, an increase in their productivity being 1.5–9.9%. The obtained research results are the basis for forecasting the development of sunflower hybrid crops with further measurement of the crop productivity that allows establishing a probable level of efficiency of sunflower hybrid production by agricultural producers under the climatic conditions of the Steppe zone.

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