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Spatio-temporal research on the effect of pre-crops on winter wheat growth and productivity to the BBCH scale in soil-climatic conditions of the steppe zone of Ukraine

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Abstract

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Spatio-temporal processes of the pre-crop effect on winter wheat development and productivity in natural-climatic conditions of the Steppe zone were examined on the basis of the data of the decoded satellite imagery series of the spacecraft Sentinel 2 and calculations of NDVI values. The processes of winter wheat growth were studied in accordance with the unified BBCH scale. It was established that winter wheat plants on the plot with pea as a pre-crop grew 1.6 times more actively than on the plot with a grain crop (spring barley) as a pre-crop and 1.7 times more actively than on the plot with sunflower as a pre-crop. It accounts for an increase in winter wheat productivity – 1.43 and 1.56 times, respectively. Winter wheat productivity on the plot with pea as a pre-crop equaled 4.65 t/ha, on the plot with a grain crop (spring barley) as a pre-crop – 3.24 t/ha, on the plot with sunflower as a pre-crop – 2.98 t/ha. Mathematical models of forecasting winter wheat productivity depending on the pre-crop were created. The credibility of modelling was 99.9%.

Keywords: winter wheat; pre-crop; productivity; climate; NDVI, forecasting

Introduction

Crop rotations are an important factor affecting physical-chemical properties of soils, intensity of crop growth and productivity, since they determine the course of technological processes (Theron et al., 2022; Liu et al., 2023). It is highly important to substantiate them in terms of ecological restoration in the Steppe zone of Ukraine (the zone of extreme agriculture), characterized by a low level of moisture supply and high temperatures (Lisetskii & Pichura, 2016;

Dudiak et al., 2019; Pichura et al., 2022). It was established that appropriate application of crop rotations improves micro-climate of farmlands (Schöning et al., 2023), contributes to accumulation of macro-elements (Breus & Skok, 2021; Breus & Yevtushenko, 2023; Xing et al., 2022) and moisture in soil (Domaratskiy et al., 2018; Wang et al., 2023), increases intensity of photosynthetic processes, production of chlorophyll content in leaves, enlarges the area of photosynthetic surface during the growing season (Jia et al., 2014), reduces the level of moisture evaporation from soil (Davis et al., 2017), facilitates moisture accumulation in plants and improves their stress-resistance under high temperatures (Nielsen et al., 2005; Domaratskiy et al., 2022).

Scientific studies prove optimality of a four-field rotation (varying from a three- to a five-field rotation) (Markovska, 2018). There should be a five- or an eight-field rotation in growing flax, lupine, sunflower, cabbage or melons. High yields are determined by crop rotations (Dogliotti et al., 2003), since a pre-crop assists in maintaining moisture regime that is especially important under conditions of the Steppe. It was found that plants absorb 550–700 m^3 of moisture for generation of 1 ton of dry corn yield for grain and sorghum, winter grain crops – 800–1100 m^3, pea – 1000-1300 m^3, sunflower – 1100–1500 m^3 of moisture from soil during the growing season in the Steppe zone (Tsilyurik & Rumbach, 2020; Pichura et al., 2023a). Black fallow is highly efficient in terms of moisture accumulation in soil, therefore, in the zone of extreme agriculture, in forecasted periods of low rainfall, it is recommended that black fallow be involved in crop rotation to improve productivity of agrocenoses (Wang et al., 2021; Gao et al., 2023).

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

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

Violation of crop rotation rules causes weed growth, spread of pests and diseases, a reduction in effectiveness of chemical plant protection products (Kussul et al., 2022; Korkhova et al., 2023). For instance, winter wheat sown after winter wheat as a pre-crop is 1.4–1.7 times more susceptible to root rots, 1.5–2 times – to brown and yellow rust, 1.3–4 times – to snow mold (Zinchenko et al., 2001; Bad'orna et al., 2009). Weed growth is 10 times higher. It is necessary to highlight that the productivity of winter wheat monocrop decreases 2–3 times in the fourth year, and the substantiated pre-crop ensures an increase in its productivity by 7.5–26.0% (Bugajov et al., 2021; Pyndus et al., 2022). In addition to an increase in productivity, the quality of agricultural products and environmental conditions improve.

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

Material and Methods

The research territory and climatic conditions

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

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

Soil-morphometric characteristic of the experimental field

The experimental field is located in loess soils, medium- and slightly-eroded common black soils with low humus content. Humus content in soils ranges from 2.25% to 3.45%, the depth of humus horizon is 50–60 cm, soil density is 1.0–0.2 g/cm^3. The reaction of soil solution is close to neutral (pH 7.0),

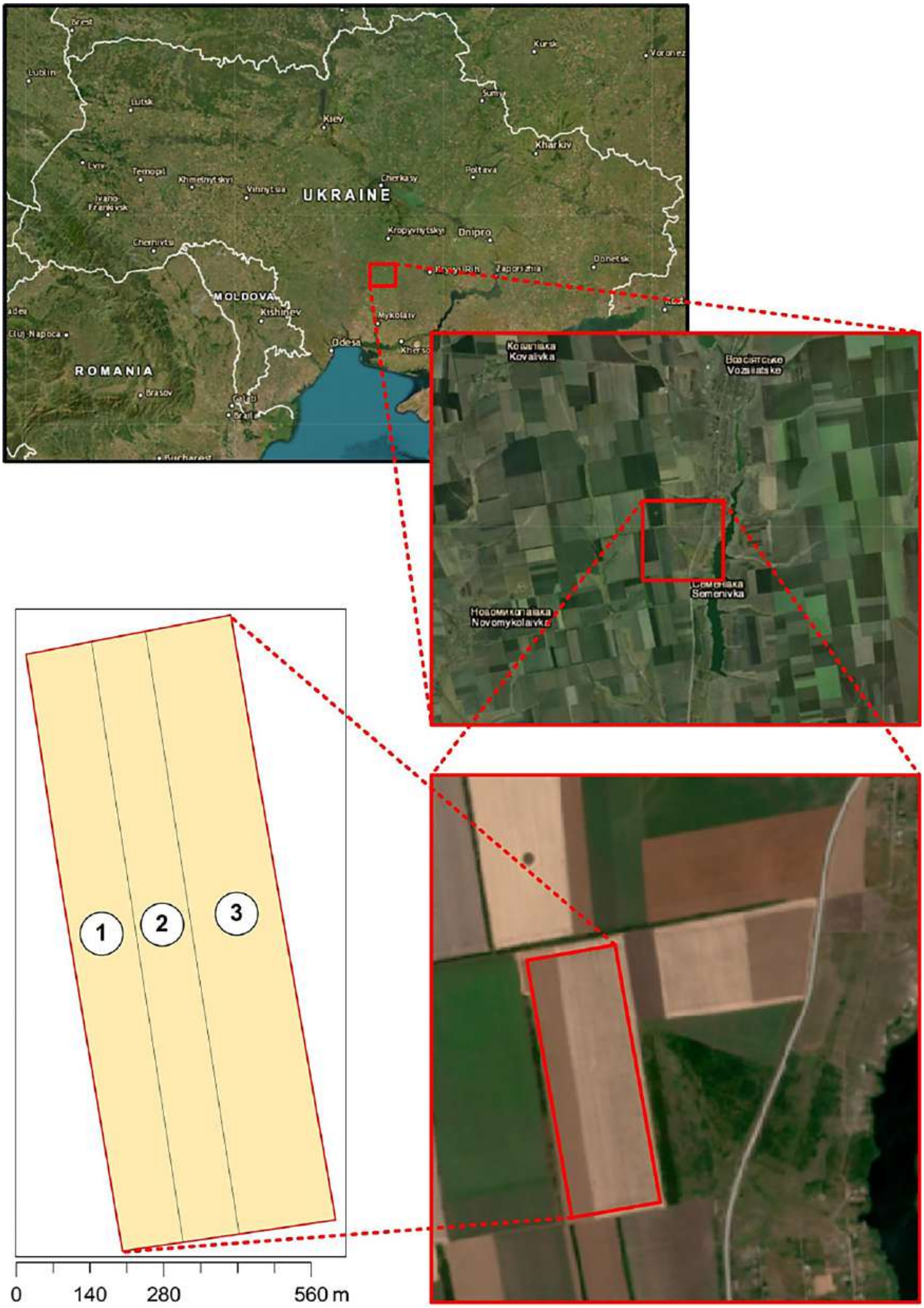


Fig. 1. Location of the experimental field and the arrangement of winter wheat crops of the variety Driada 1 according to pre-crops: 1 – pea; 2 – grain crop (spring barley); 3 – sunflower

the amount of absorbed alkali equals 34-38 mg equiv. per 100 g of soil, the degree of saturation with alkali is 95.7%. In terms of the content of mobile macro-elements, the soil of the experimental field is characterized by a medium content of nitrate nitrogen in the soil layer of 0…20 cm – 86.0 mg/kg and that of mobile phosphorous – 58 mg/kg and a very high content of exchangeable potassium – 160.0 mg/kg of soil. The average content of macro-elements equals: manganese – 4.6 mg/kg, zinc – 0.32 mg/kg, cobalt – within 0.02–1.15 mg/kg, cuprum – 0.08–0.59 mg/kg, cadmium – 0.084–0.756 mg/kg, lead – 0.52–5.57 mg/kg, mercury – 0.012 mg/kg of soil.

The terrain affects the distribution of moisture, temperature of soil surface, climate energy for soil formation, determines micro-climatic conditions of crop yield formation within individual fields. Terrain morphology determines the character and intensity of erosion processes resulting in spa-

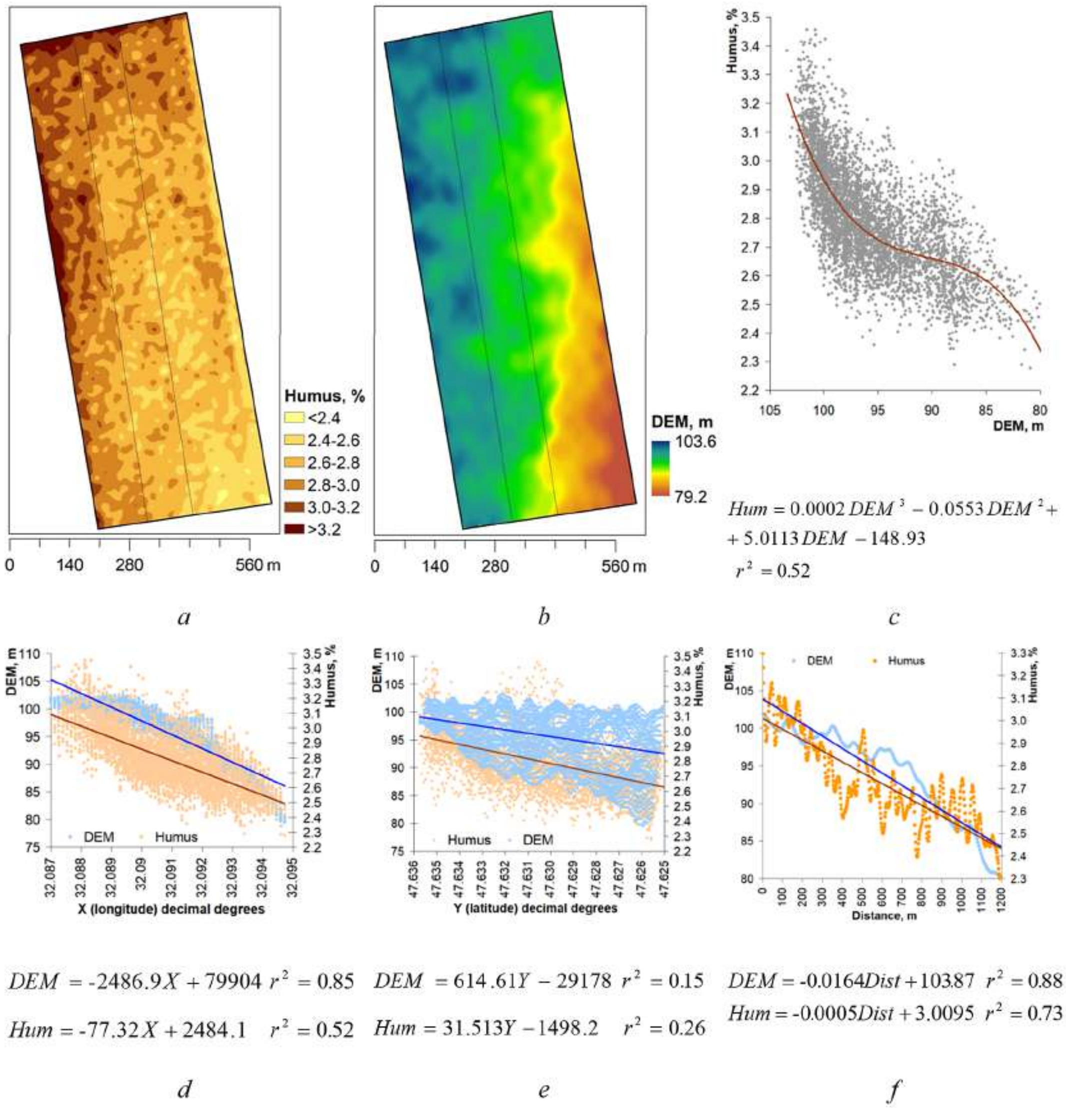


Figure 2. Soil-morphometric characteristic of the experimental field: *a* **– a cartogram of humus distribution (%),** *b* **– a digital model of the terrain (m),** *c* **– spatial differentiation of humus content in the soil layer of 0...20 cm depending on the terrain of the field;** *d* **– a change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

tial redistribution of agro-chemical elements of soil cover and emergence of parent material on the surface. It is worth mentioning that humus is one of the main characteristics of soil fertility and an indicator of farming efficiency. Decoded satellite imagery of the spacecraft Sentinel 2 and comparison of spectral characteristics with the results of the field research on soil fertility allowed creating a cartogram of humus spatial distribution in the upper layer of 0…20 cm of soil (Figure 2a). The cartogram of humus distribution was created using the data of the satellite image dated September 16, 2021, the date of the image creation was characterized by dry soil without vegetation and a lack of moisture for 12–15 days that ensured its accuracy and credibility.

Humus content within the field ranges from 2.25% to 3.45%, the average value is 2.8%. Soil cover disturbance and spatio-temporal differentiation of humus content result from agro-technological processes characterized by intensity of land use. The research established that spatial distribution of humus content in the upper soil layer of 0…20 cm is determined by the terrain and signs of water erosion processes. The terrain of the experimental field lowers from the north-west toward the south-eats within 103.6–79.2 m (Figure 2b). We established spatial differentiation of humus content in the soil depending on changes in the terrain of the field (Figure 2c), the level of correlation being r = 0.72. It was found that the field lowering by 1 m is accompanied by a decline in humus content by 0.027% (Figure 2c, f). Thus, the dependence of a change in humus content on a geographic location of each part of the field and the terrain itself was established (Figure 2d, e). Humus content is an important indicator of natural soil fertility and an indicator for applying fertilizers, forecasting crop yields, developing methods for improving farming practices.

Agro-technological characteristic of growing winter wheat

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

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

Stages	Agro-technological practices, specificity	Plot 1 (pea pre-crop)	Plot 2 (spring barley pre-crop)	Plot 3 (sunflower pre-crop)
Soil tillage	Practice, dates, requirements (depth), notes	• Disk harrowing of 5–6 cm deep (after harvesting the pre-crop, the 2nd decade of June); • Disk plowing of 16–18 cm deep (the 1st decade of August); • tillage of 7–8 cm deep (the 3rd decade of August); • pre-sowing tillage of 5–6 cm deep (the 3rd decade of September).		• After harvesting the pre-crop, the 3rd decade of August, disk plowing to 18 cm deep with simultaneous packing down the soil to compress it before sowing winter wheat; • Pre-sowing tillage of 5–6 cm deep (the 3rd decade of September).
Seed preparation	Characteristic: generation, emergence, varietal purity, moisture, seed treatment, seeding rate	Sowing certified seeds of the variety Driada of the first generation, their sowing quality complies with the State standards of Ukraine (DSTU 3240-93. Agricultural crop seeds, varietal and sowing characteristics). Winter wheat seeds were treated with the preparation containing the active material Tebukonazol 750 g/kg, 10 days before sowing in the field experiment.		
Sowing	Sowing dates, sowing method, equipment, seedbed depth	Seeds were planted with a grain planter with row spacing of 15 cm (СЗ-5.4) on September 29, the variety Driada 1, its originator is the RPC «Driada LLC», Kherson, Ukraine. The seeding rate was 3.5 mln. of germinating seeds per hectare. The depth of the seedbed was 5-6 cm.		
Caring for crops	Autumn: fight with rodents, spraying. Spring: feeding (fertilizer, rate), feeding dates. Treatment (diseases, herbicides), treatment dates, preparation, equipment, treatment method	Autumn care for the crops involved protection from mouse-like rodents by means of scattering traps treated with a rodenticide with Brodifakum as an active material, 0.25%. Spring care for the crops involved: • Early spring feeding of winter wheat plants with mineral fertilizers (nitrate) with the rate N_{30} at the beginning of spring growth; • Herbicide to struggle with annual bilobate weeds in agrocenosis (the active material is *Thifensulfuron-methyl*, 300 g/kg + tribenuron-methyl, 300 g/kg + florasulam, 100 g/kg) was applied at the plant growth stage BBCH 30-34; • All insecticide treatments of agrocenosis were performed according to the forecasts of entomophage development (at the stage of grain milk-wax ripeness, insecticide treatment of the crops was performed with the preparation with chlorpyrifos as an active material – 500 g/l and cypermethrin – 50 g/l to prevent the shield bug – ***Eurygaster integriceps*** *Put.*).		
Harvesting	Harvesting dates, harvesting method, grain quality	Winter wheat was harvested in the first decade of July, the grain moisture content being 15%. The yield registration and its structure were performed mechanically, by reaping plants from the registered area with the combine harvester Claas Lexion 760 and recalculating grain moisture content by 14% and impurities – 2%. The area of the registered plots equaled 4500 m^2 .		

Methods for decoding space imagery and spatial analysis

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

The value of NDVI was calculated by the formula:

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

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

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

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

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

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

$$\mathrm{NDWI} = \frac{NIR - SWIR}{NIR + SWIR}, \quad (2)$$

where *NIR* – the visible and near infrared band (Sentinel 2 – Band 8A, 865 nm), *SWIR* – shortwave infrared radiation (Sentinel 2 – Band 11, 1610 nm).

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

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

$$\mathrm{NDSI} = \frac{Green - SWIR}{Green + SWIR}, \quad (3)$$

where *Green* – the green band of the electromagnetic spectrum (Sentinel 2 – Band 3, 560 nm), *SWIR* – shortwave infrared radiation (Sentinel 2 – Band 11, 1610 nm).

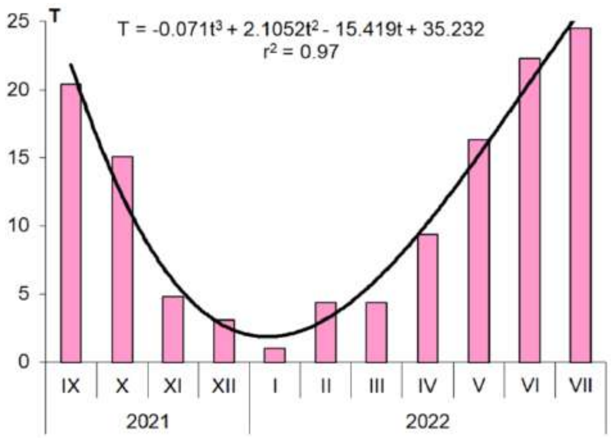
A pixel with the NDSI value > 0.0 is considered to contain snow, a pixel with NDSI <= 0.0 is the land surface without snow cover.

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

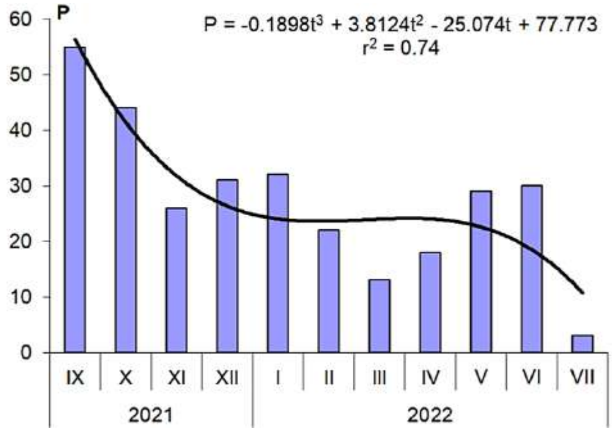
Results and Discussion

Analysis of climatic conditions of the research

The zonal conditions of the research are characterized by semi-arid natural-climatic conditions. The mean air tempera-



a)



b)

Fig. 3. Climatic conditions of the growing season of winter wheat (2021–2022): a – the average monthly temperature (T, °C); the amount of precipitation (P, mm)

ture (T, °C) in the growing season of the winter wheat variety Driada 1 was 11.4°C (Figure 3a), the standard deviation equaled 8.4°C, the variance level was 74.8%. A high level of the air temperature variance was characterized by seasonal fluctuations. The total precipitation (P, mm) in the growing season of winter wheat was 303 mm (Figure 3b), the standard deviation equaled 14.1°C, the variance level was 4.7%. Autumn of 2021 in the crop growing season was characterized by sufficient moisture and a moderate temperature regime for the Steppe zone. The total precipitation was 125 mm, the average monthly temperature varied from 20.4°C in September to 4.8°C in November, 2021. In this period the air temperature had synchronous fluctuations with precipitation that ensured high germination energy and active photosynthetic processes of the plant development before winter anabiosis.

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

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

Examination of winter wheat growth

Winter wheat growth, activeness of photosynthetic processes, production of chlorophyll content and the formation of yield structural elements depend on soil-climatic conditions of the territory, crop rotation, characteristics of pre-crops and efficiency of agricultural technologies. Satellite imagery decoding and calculation of NDVI values (Figures 4 & 5) allow establishing specificity of plant growth and development at crucial macro-stages of yield formation, that makes it possible to adjust agro-technological operations which can result in an increase in agricultural crop productivity by 40–60%.

Winter crop yields are programmed at the stage of adjusting seeding rates, the recommended seeding rate for winter wheat in the experimental zone is 3.5 million seeds per hectare. An increase in the seeding rate can cause competition of

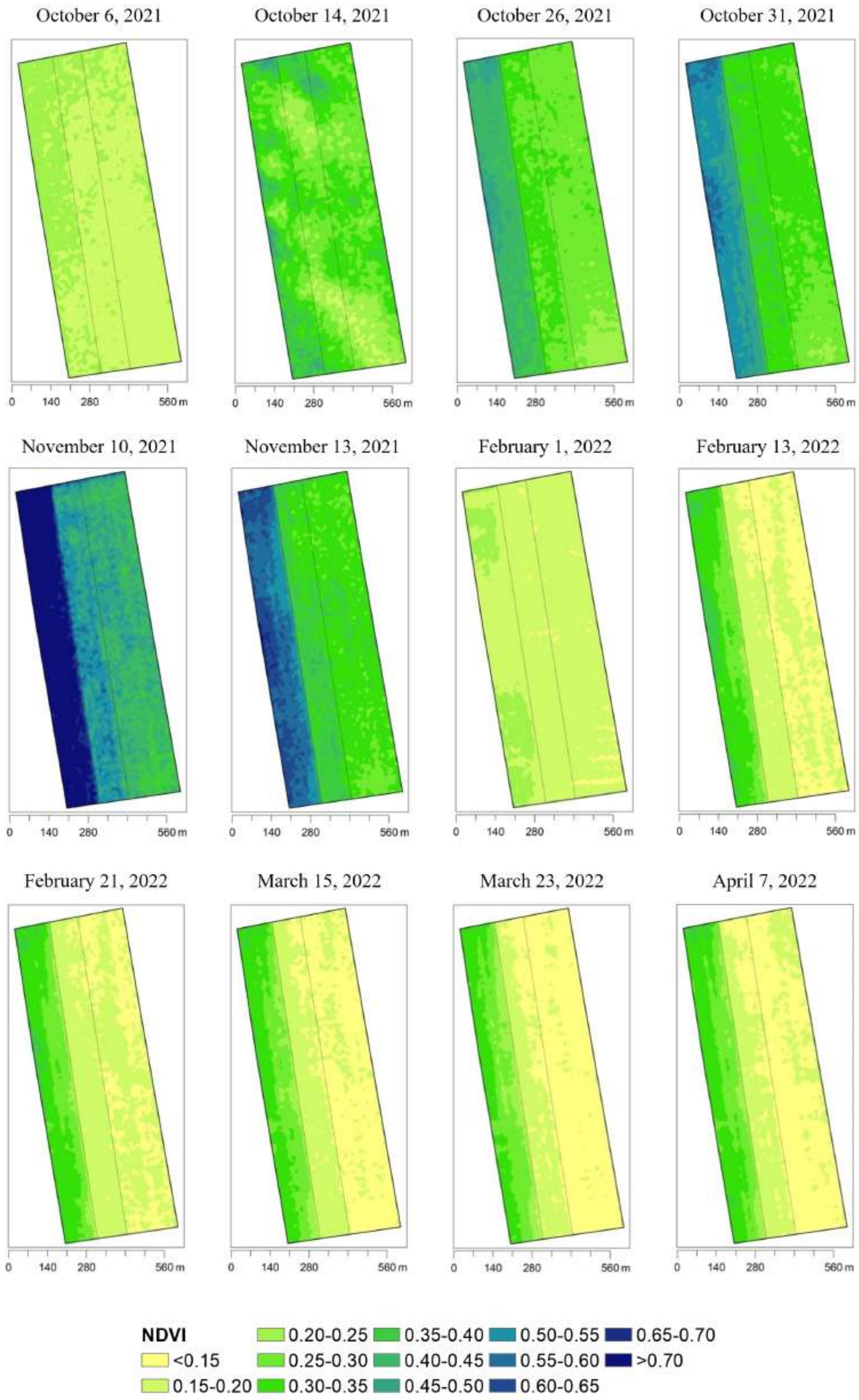


Fig. 4. Seasonal differentiation of the NDVI values of the winter wheat variety Driada 1 in the experimental field at the macro-stages BBCH 00-30

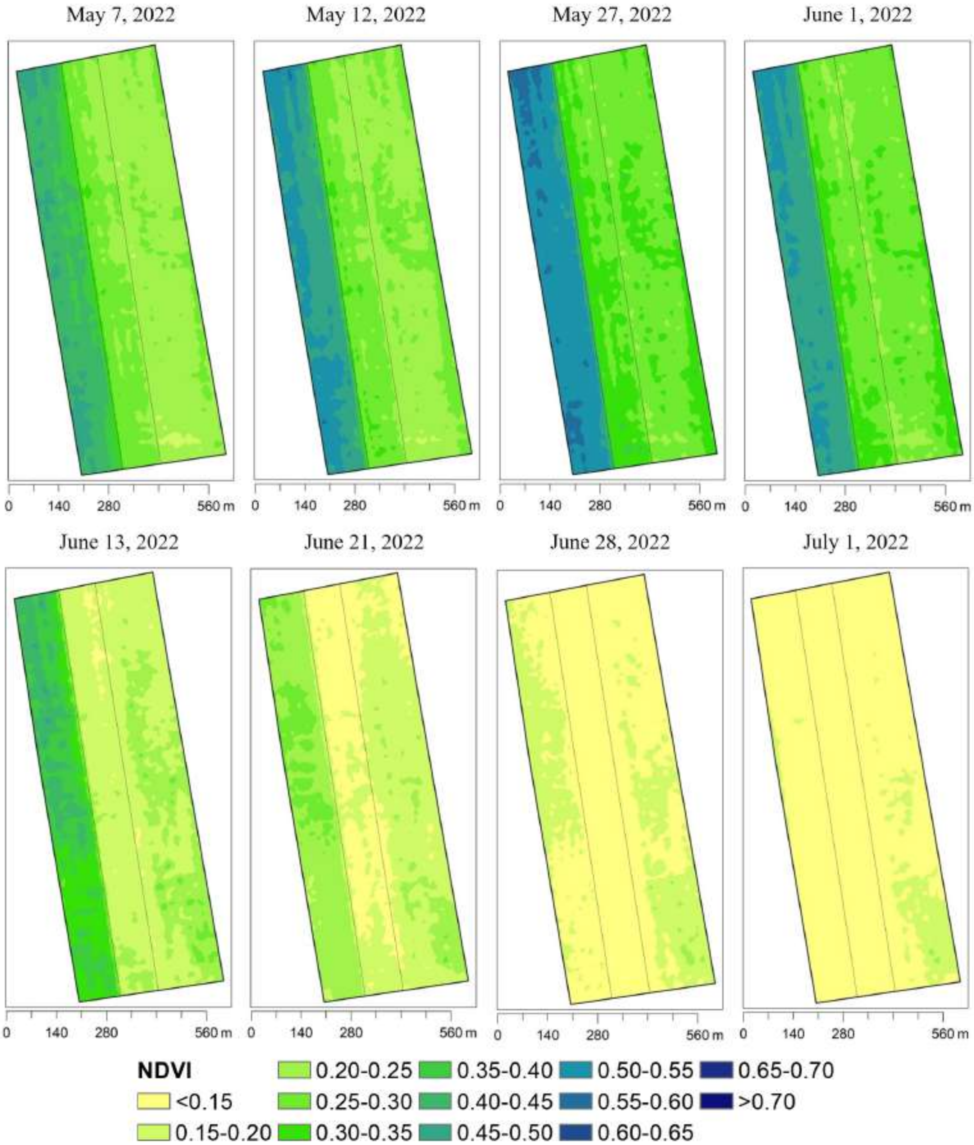


Fig. 5. Seasonal differentiation of the NDVI values of the winter wheat variety Driada 1 in the experimental field at the macro-stages BBCH 31-99

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

It was established that autumn growth at the macro-stages of leaf development (BBCH 10-19) and tillering (BBCH 20-29) depends on the pre-crop. Favorable conditions for autumn plant development were registered on Plot 1, the NDVI value at the macro-stage BBCH 10-19 increased from 0.19-0.53 to 0.32–0.56 (from October 10 to October 27, 2021). Under

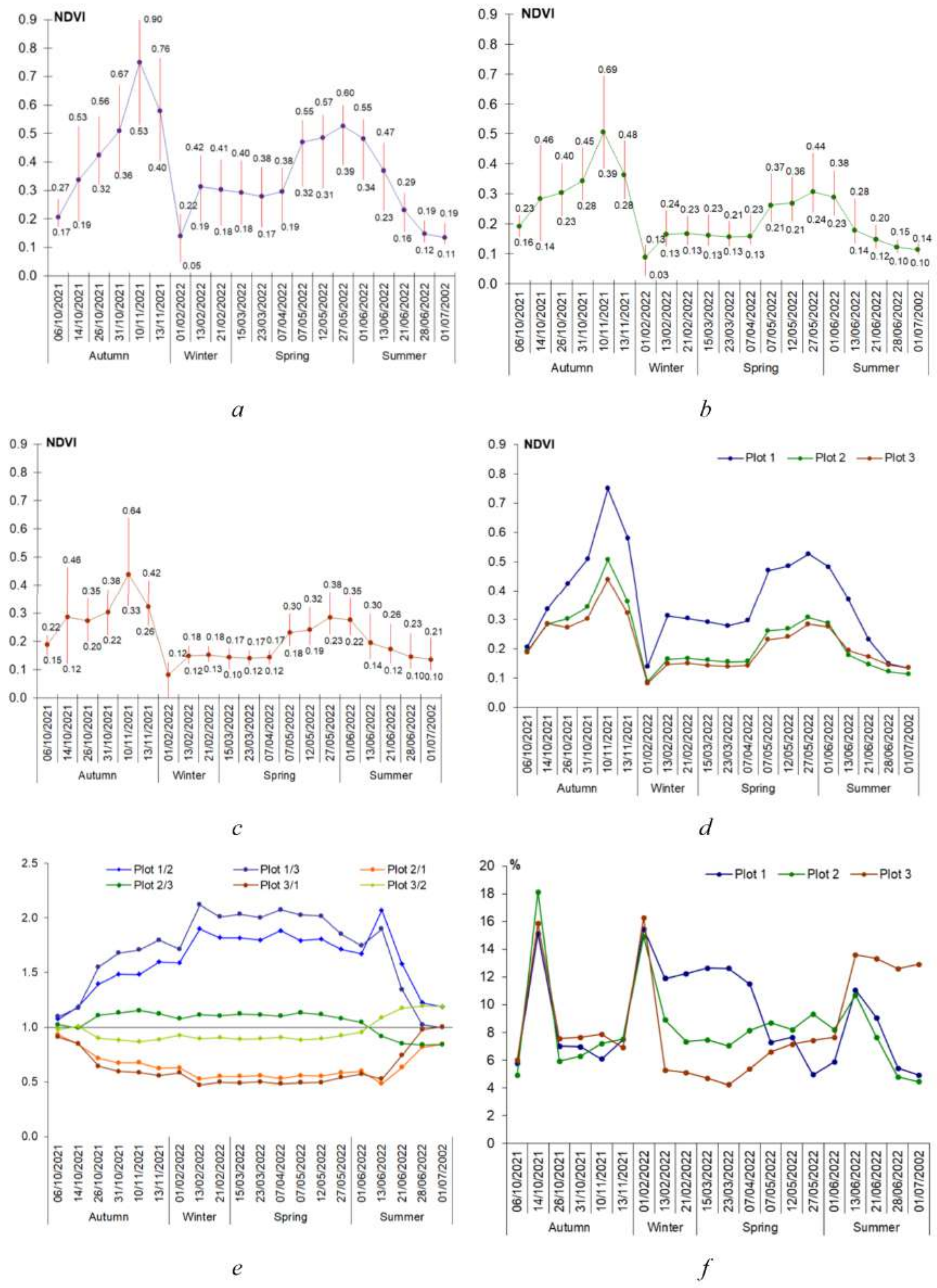


Fig. 6. Seasonal distribution of the NDVI values of the winter wheat variety Driada 1: a – Plot 1 (pea as a pre-crop); *b* – Plot 2 (a grain crop (spring barley) as a pre-crop); *c* – Plot 3 (sunflower as a pre-crop); *d* – the average NDVI values; *e* – the correlation of the NDVI values; *f* – the variance of the NDVI values

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

On Plot 2 stunted growth was observed that prolonged the macro-stages of leaf development (BBCH 10-19) in comparison with the intensity of wheat development in the first field. The duration of the plant growth at the macro-stage BBCH 10-19 equaled 30 days (October 7 – November 7, 2021). The NDVI values at the stage of leaf development varied from 0.14–0.46 to 0.28–0.45 (Figure 4, Figure 6b). The plants on Plot 2 entered winter anabiosis at the macro-stage BBCH 21 (the beginning of tillering and formation of the first tiller). On November 10, 2021 the maximum NDVI value was registered in autumn growth of winter wheat that varied from 0.39 to 0.69.

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

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

Satellite imagery decoding by the Normalized Difference Snow Index (NDSI) and Normalized Difference Water Index (NDWI) on February 1, 2022 (Figure 7) allowed establishing that a decrease in the NDVI value was determined by snow cover on 25% of the field that changed spectral reflectance characteristics in the near infrared and red bands of the electromagnetic spectrum. On February 13 and February 21, 2022 the satellite images did not register snow cover, that allowed performing accurate calculations of NDVI values for a typical period of winter anabiosis of winter wheat. The

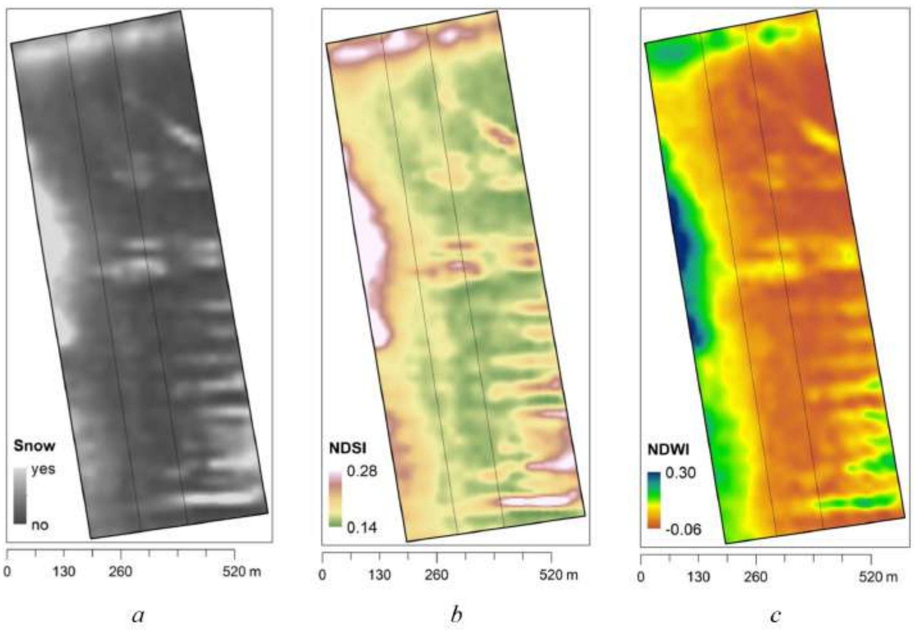


Fig. 7. Indication of the presence of snow cover (NDSI) and moisture (NDWI) of the experimental field on February 1, 2022: a – presence of snow cover; *b* – Normalized Difference Snow Index (NDSI); *c* – Normalized Difference Water Index (NDWI)

NDVI values on Plot 1 varied from 0.18 to 0.42, on Plot 2 – 0.13-0.24, on Plot 3 – from 0.12 to 0.18. It was established that the pre-crop has a considerable impact on activeness of photosynthetic processes during winter anabiosis and plant stress-resistance to climatic conditions.

Winter wheat started resuming spring growth on March 15, 2022 which lasted till April 7, 2022, the NDVI values on Plot 1 varied from 0.17 to 0.38, on Plot 2 – 0.13–0.21, Plot 3 – 0.12–0.17. It is worth mentioning that autumn and spring tillering and the beginning of booting BBCH 30 are important for the formation of productive tillers, ear elements and the amount of future crop yield. In particular, the process of the formation of grain-bearing elements of the ear and the number of grains per ear starts at the end of tillering. At the macro-stage BBCH 30 elongation and segmentation of the growth apex of the second order occur, the formation of the ear rhachis and spikelets in it lasts. This is a sign of moving from the vegetative to generative stage of grain crops. On April 7, 2022 better starting conditions for increasing photosynthetic surface were registered in the winter wheat plants located on Plot 1, the NDVI values equaled 0.19–0.38. Worse conditions were observed in the plants on Plot 2, the NDVI values being 0.13–0.23, and on Plot 3, the NDVI values being 0.12–0.17.

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

To protect leaves of grain crops using chemical control is an important agro-technological task, since leaf diseases are a cause of a decrease in the area of photosynthetic surface during the vegetative stage, that is a reason for too early cessation of photosynthetic processes, a reduction in the activeness of chlorophyll production, crop yield and productivity. Therefore, efficient absorption of photosynthetic radiation and an active increase in the biomass of grain crops begins with the emergence of the third leaf (BBCH 32) and lasts till the end of milk ripeness (BBCH 79). Therefore, in this period, realization of genetic potential of winter wheat depends on the effectiveness of agro-technological practices aimed at protecting plants against diseases, fertilization regime and moisture retention. In particular, the state of productive shoots is important at the macro-stages of stem elongation (BBCH 30-39) and booting (BBCH 41-49), that insures highly-productive formation of plant photosynthetic surface. The number of productive stems per unit area (m^2), the number of spikelets and grains per ear, the weight of 1000 seeds (grain-unit) are important indicators of winter wheat productivity. The following results were obtained on the experimental plots: Plot 1 – the yield was 4.65 t/ha, the number of productive stems was 390 pcs/m^2, the weight of 1000 seeds – 42.5 g, the number of grains per ear – 30 pcs, the weight of grain per ear – 1.27 g; Plot 2 – the yield was 3.24 t/ha, the number of productive stems was 320 pcs/m^2, the weight of 1000 seeds – 39.0 g, the number of grains per ear – 27 pcs, the weight of grain per ear – 1.05 g; Plot 3 – the yield was 2.98 t/ha, the weight of 1000 seeds – 39.0 g, the number of productive stems was 305 pcs/m^2, the number of grains per ear – 26 pcs, the weight of grain per ear – 1.01 g.

It was established that after heading (BBCH 37-39) in the flag leaf and the pre-flag leaf (BBCH 31-33), and also in the ear (BBCH 59) there occurs synthesis of reserve material which is transported and accumulated in the kernel endosperm. The weight of a grain and the weight of 1000 grains depend on the efficiency of this physiological process. The formation of 45% of the total grain weight is supported by assimilates formed in the flag leaf. The pre-flag leaf, the second, third and fourth leaves form grains to 35%, the rest 20% is formed from accumulated assimilates and synthesized in the ear.

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

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

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

Forecasting winter wheat yield

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

$$NDVI_{cy} = 0.03NDVI_{BBCH31} + 0.09NDVI_{BBCH32} + 0.23NDVI_{BBCH33} + 0.45NDVI_{BBCH39} + 0.2NDVI_{BBCH59} \quad (4)$$

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

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

These data were used to create cartograms of spatial differentiation of winter wheat yields (CY) of the variety Driada 1 (Figure 9c) with regard to the distribution of the standardized $NDVI_{cy}$ values by the formula:

$$CY = \frac{NDVIi_{cy}}{Aver(NDVIi_{cy})} . Aver(CY_i) \quad (5)$$

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

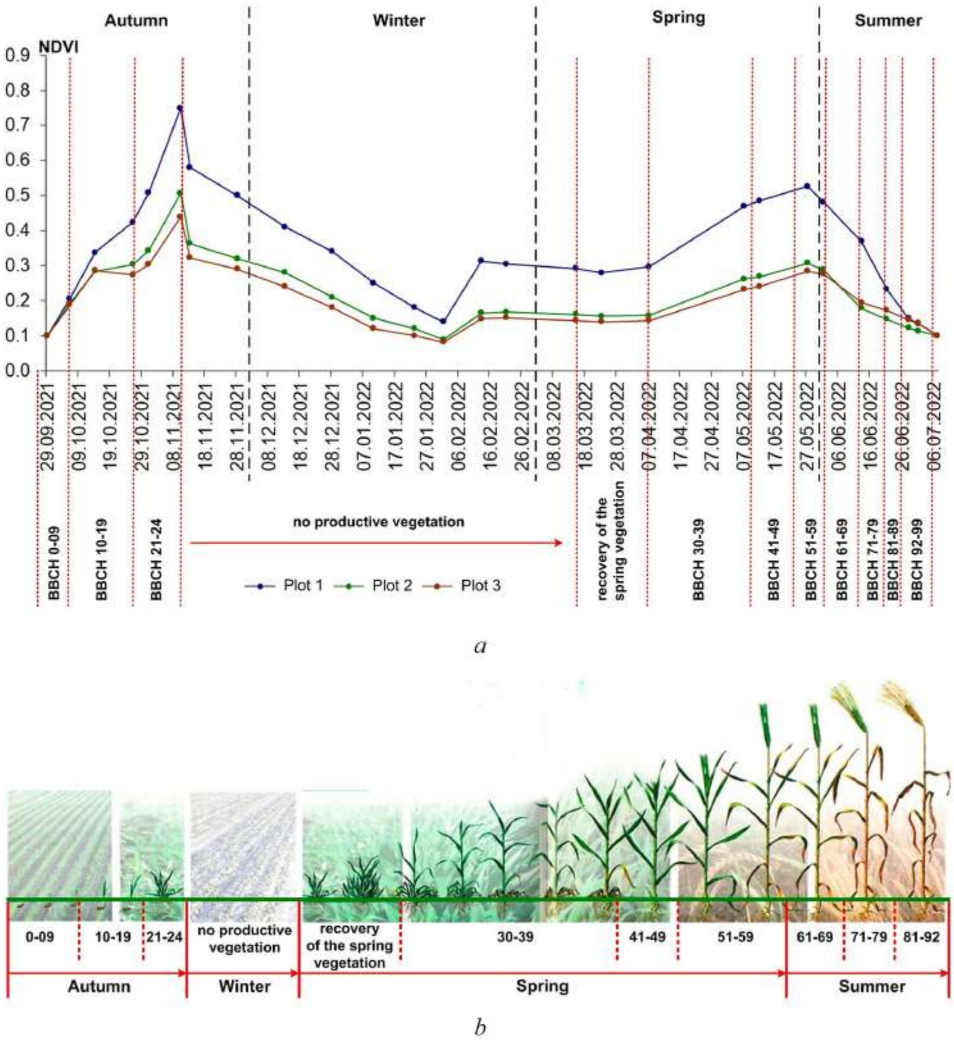


Fig. 8. Changes in NDVI (a) and visualization (b) of winter wheat development in accordance with the unified BBCH scale

ter wheat yields within individual experimental plots of the pre-crop.

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

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

Pea as a pre-crop:

$$Y_1 = 1.735NDVI_{32} + 2.040NDVI_{33} + 4.813NDVI_{39} + 2.139NDVI_{59},\ r^2 = 0.999 \quad (6)$$

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

$$Y_2 = 2.238NDVI_{32} + 2.420NDVI_{33} + 5.925NDVI_{39} + 2.633NDVI_{59},\ r^2 = 0.999 \quad (7)$$

Sunflower as a pre-crop:

$$Y_3 = 2.180NDVI_{32} + 2.550NDVI_{33} + 6.030NDVI_{39} + 2.680NDVI_{59},\ r^2 = 0.999 \quad (8)$$

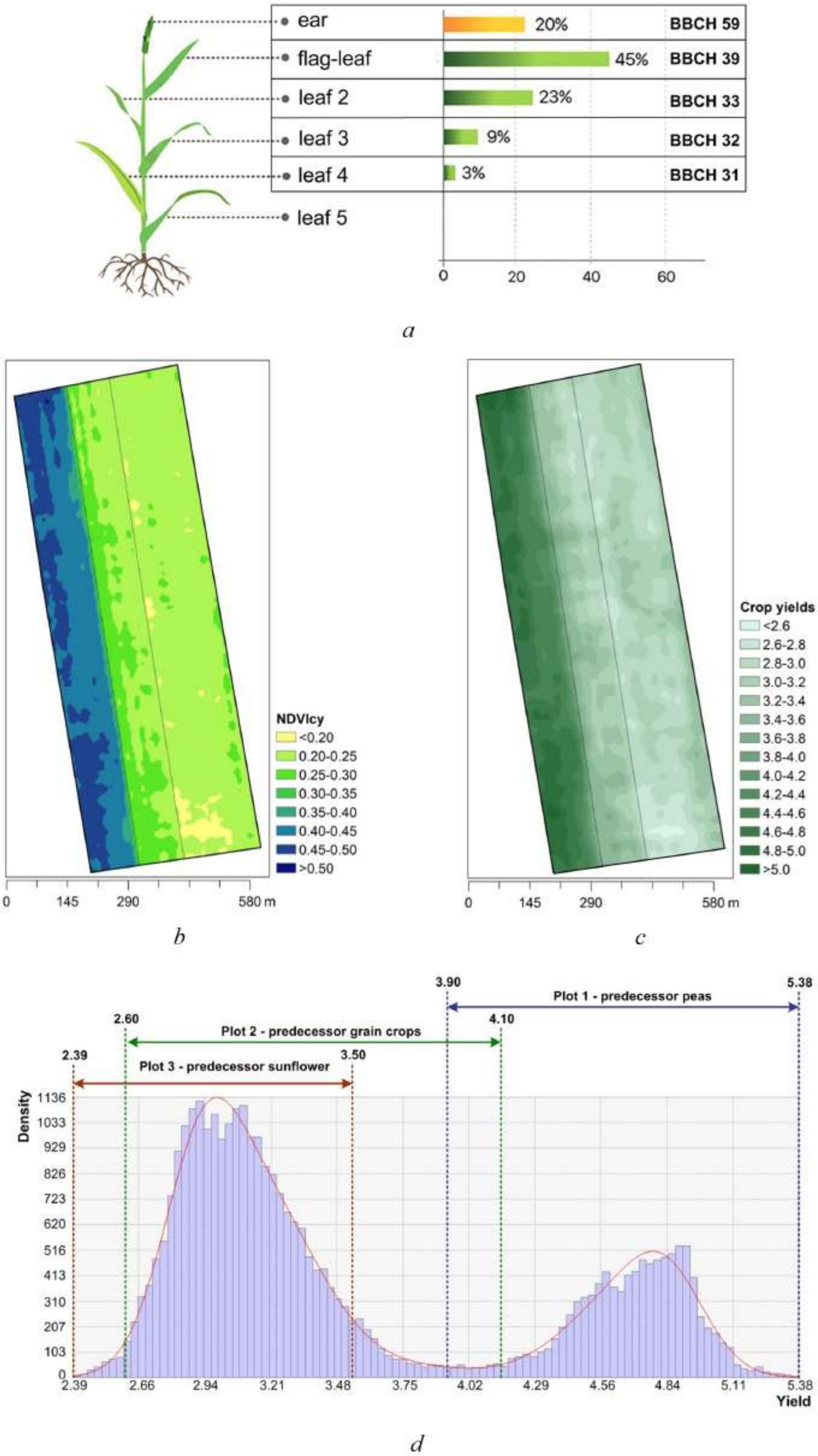


Fig. 9. Yield formation of the winter wheat variety Driada 1: *a* – crucial stages of yield formation, *b* – cartograms of distribution of the generalized NDVI data; *c* – cartogram of yield distribution; *d* – histogram of yield distribution

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

Conclusion

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

It was proved that the formation of 45% of the total grain weight is provided by assimilates in the flag leaf. The pre-flag leaf, the second, third and fourth leaves take part in the formation of the grain by 35%, the rest 20% is synthesized from accumulated assimilates in the ear. The weight of each grain, the weight of 1000 seeds and crop yields depend on the efficiency of synthesis of reserve substances which are further transported and accumulated in the kernel endosperm. Therefore, mathematical models of forecasting winter wheat productivity depending on the pre-crop were created on the basis of the cartograms of spatial differentiation of NDVI values, during the period of this physiological process at the macro-stages BBCH 32, BBCH 33, BBCH 39 and BBCH 59. The credibility of modelling was 99.9%. The obtained research results can be used to improve methods for studying agricultural crop growth, substantiate crop-rotations and pre-crops, determine effectiveness of agro-technological practices and forecast winter wheat productivity in soil-climatic conditions of the Steppe zone of Ukraine.

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