JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(3), 253–271
https://doi.org/10.12911/22998993/181553
ISSN 2299–8993, License CC-BY 4.0

Received: 2023.12.03
Accepted: 2024.01.07
Published: 2024.01.29

The Impact of Pre-Crops on the Formation of Water Balance in Winter Wheat Agrocenosis and Soil Moisture in the Steppe Zone

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ABSTRACT

Under climate change, the issue of selection and correction of crop cultivation systems in the zone of moisture deficit and risky farming to ensure profitability of production is still topical. In particular, crop rotations are a practice aimed at increasing resistance of soil systems to abiotic and biotic stresses in the zone of moisture deficit. Therefore, the purpose of the research is to identify spatio-temporal regularities of vegetative formation of water balance in winter wheat agrocenoses depending on a pre-crop according to the unified BBCH scale. Spatio-temporal processes of vegetation and water balance formation in winter wheat agrocenosis depending on a pre-crop according to the unified BBCH scale were examined on the basis of the data of decoded satellite image series of the spacecraft Sentinel and calculation of the NDWI and the NDVI values. The research was conducted in the natural-climatic conditions of the Steppe zone of Ukraine, in the territory of Yelanets district, Mykolaiv region, during the vegetative phase of winter wheat variety Driada 1: autumn 2021 and winter, spring and the beginning of summer 2022. It was established that activeness of water balance formation in winter wheat agrocenosis with pea as a pre-crop according to seasonal-phenological stages of plant growth is 3.0–9.0 times higher than with a grain crop (spring barley) and sunflower as pre-crops. In particular, with pea as a pre-crop, the NDVI vegetation of winter wheat plants is 1.6–1.7 times more intensive, the rate of moisture supply NDWI in the plant leaf at the macro-stages BBCH 10–61 is 1.54 and 1.82 times higher, productivity is 1.43–1.56 times higher. We observed a 30.5–34.3% reduction in water consumption for the formation of a ton of winter wheat grain with pea as a pre-crop in comparison with other pre-crops that resulted in an increase in productive moisture reserves at the end of vegetation in a meter soil layer by 20%. It was established that using pea as a pre-crop has economic and environmental benefits that manifest themselves in increasing resistance of soil systems, a reduction in environmental pollution and a rise in profitability of production.

Keywords: winter wheat, crop rotation, NDWI, NDVI, productive moisture, water consumption, productivity, satellite images.

INTRODUCTION

Food security, which is a determining factor of global stability, is an important task of agricultural production. The main reasons for agricultural producers' concern are climate changes, whose intensification complicates farming. It is important to highlight that, over the past years, introduction of adaptive technologies and use of stress-resistant varieties and hybrids of agricultural crops are difficult to access for small farms because of high prices for seeds, plant protection products, fuels and lubricants and high depreciation of machines. Large enterprises took dominating positions on the market of agricultural products that has led to deterioration of ecological condition of land and water resources, caused by introduction of intensive technologies (Breus and Skok 2021; Breus and Yevtushenko 2022; Dudiak et al., 2020, 2021; Pichura et al., 2021).

Intensive agriculture means introducing technologies for growing agricultural crops aimed at improving their productivity (Bruns, 2012; Siddique et al., 2021) that has become a cause of increasing genetic homogeneity and similarity of agricultural landscapes (Hufnagel et al., 2020; Sehgal et al., 2023). It was established (USDA-ERS… 2012; Skok et al., 2023) that application of balanced systems of crop rotations involving rotation of crops with high and low levels of residues in one field is an important method for coping with such problems. Crop rotations including legume crops contribute to an increase in productivity of a subsequent crop, maintaining nitrogen balance due to its fixation in soil (Claassen et al., 2018). Therefore, application of crop rotations increases resistance of soil systems to abiotic and biotic stresses (Reckling et al., 2016; Li et al., 2019;, Sanford et al., 2021). Consequently, crop rotations improve plant growth, water balance of agrocenoses, water-table and soil moisture content and contribute to a rise in agricultural crop productivity (Stetina et al., 2007; Bennett et al., 2012).

It was found (Albers et al., 2017; Knapp and Heijden, 2018; Domaratskiy et al., 2018, 2019) that the main conditions for vegetation are a climatic factor, crop rotations, the amount of nutrients in soil and the level of agro-technological practices. In particular, a pre-crop affects the level of accumulation of nutrients important for plants in soil, moisture content in soil, sowing dates, intensity of vegetation, formation of morphological properties and leaf water balance, the rate of plant metabolism and photosynthesis (Berzsenyi, 2000; Yang et al., 2022; Breus and Yevtushenko, 2023). An effective pre-crop improves a field micro-climate, that is maintained by an increase in leaf surface of crops and a reduction in evaporation of moisture from soil surface (Ray et al., 2015; Berti and Mulligan, 2016). It was proved (Firn et al., 2019) that functional characteristics of leaves directly correlate with plant growth and productivity. They affect the carbon cycle, dynamics and energy balance of natural and artificial ecosystems. Plants with small leaf area and low nitrogen content in leaves have slow photosynthetic output (Cui et al., 2020). In particular, optimization of photosynthetic, gas-exchanging, water-accumulating, filtrating and water-supplying leaf potential maintains conditions for better absorption of atmospheric carbon by plants (Deans et al., 2020).

Development of crops of a certain variety or hybrid depends on changes in the environment (Reichstein et al., 2014; Anderegg et al., 2018) and agro-technological conditions of crop cultivation. It is determined by signs of plasticity which manifests itself in the state of plant leaves (Rozendaal et al., 2006; Doughty et al., 2018; Yang et al., 2019) under the influence of biotic and abiotic factors. Well-developed plant plasticity is a result of selection and adaptation of varieties and hybrids to particular soil-climatic conditions for growing them (Domaratskiy et al., 2022; Pichura et al., 2023). In addition, plant breeding is important for agrocenosis adaptation to new climatic conditions occurring over the past 25–30 years. Therefore, understanding the processes of leaf development under changeable conditions is crucial in correcting their breeding characteristics and adaptation of agro-technological methods.

It was established (Wang et al., 2022) that moisture content in leaf tissues is an important functional characteristic of plants. Water determines bio-chemical reactions, regulates plant growth and metabolism affecting agrocenosis productivity, the carbon cycle in agro-ecosystems and adjacent territories. Water has an immediate effect on other leaf characteristics, first of all, thermo-regulation, the rate of photosynthesis and leaf surface area. A change in leaf surface area determines micro-climatic conditions for plant vegetative growth and their productivity that is important for zones with rainfall deficit and high air temperatures.

It is necessary to emphasize an increasing frequency of climate anomalies and rising risks of their negative effect. The main symptom of climate change is a drop in the level of moisture supply against a background of significant warming (Dudiak et al., 2019; Pichura et al., 2021, 2022). Moisture has become a determining factor in all soil-climatic zones of Ukraine (Korkhova et al., 2023). Consequently, the problem of retaining soil moisture and increasing plant resistance to moisture deficit is topical. In this context, it is necessary to focus on improving agro-technological methods, substantiating selection of a pre-crop for increasing nutrients in soil and creating favorable micro-climatic conditions for vegetative growth of plants, accumulating and retaining moisture in soil and leaf cells, high photosynthetic capacity of plants and agrocenosis productivity. Studies on balanced crop rotations do not have sufficient information about spatio-temporal regularities of vegetative formation of water balance in agrocenoses according to the unified BBCH (the scale of plant growth and development phases generally accepted in the world) scale that complicates substantiation of the necessity to improve the system of agricultural crop cultivation in zones of moisture deficit and risky farming. The purpose of the research in this direction is to develop recommendations and introduce necessary practices aimed at increasing the level of crop rotation efficiency for obtaining economic and environmental benefits by agricultural producers.

Agricultural crop production in the Steppe zone is characterized by three main directions: growing grain, oil-bearing and legume crops. Crop rotations with a share of grain crops up to 70–80% dominate. Grain crops mainly include winter wheat, spring barley, winter barley and corn. Therefore, regularities of vegetative formation of water balance in agrocenoses depending on a pre-crop were established using winter wheat crops under non-irrigated conditions of the Steppe zone of Ukraine.

MATERIAL AND METHODS

Research territory and climatic conditions

The research on dependence of vegetative growth, formation of water balance and productivity of winter wheat in the natural-climatic conditions of the Steppe zone of Ukraine on pre-crops was carried out in the vegetation period: autumn 2021, winter, spring, the beginning of summer 2022. The experimental field is located in the territory of Yelanets district, Mykolaiv region, Ukraine, used by the farm “Svitlana”. The total area of the experimental field equaled 46.64 ha (Fig. 1), including: Plot 1 – pea as a pre-crop, the area being 14.20 ha; Plot 2 – a grain crop (spring barley) as a pre-crop, the area being 12.20 ha, Plot 3 – sunflower as a pre-crop, the area being 20.24 ha. The experiments were conducted 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 experimental field is located on loess soils, medium- and slightly-eroded common black soils, poor in humus content, with low clay contents. Humus content in the soils ranges from 2.25% to 3.45%, the depth of a humus horizon being 50–60 cm, the soil density being 1.0–0.2 g/cm^3. The reaction of the soil solution is close to neutral (pH 7.0), the amount of absorbed alkali equals 34.0–38.0 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 micro-elements equals: manganese – 4.6 mg/kg, zinc – 0.32 mg/kg, cobalt – 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.

Actual values of near-surface air temperature (T, °C), total precipitation (P, mm) in the vegetation period of autumn 2021 and winter, spring, the beginning of summer 2022 (Mykolaiv Meteorological Station) were used to characterize the climatic conditions of winter wheat vegetation.

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

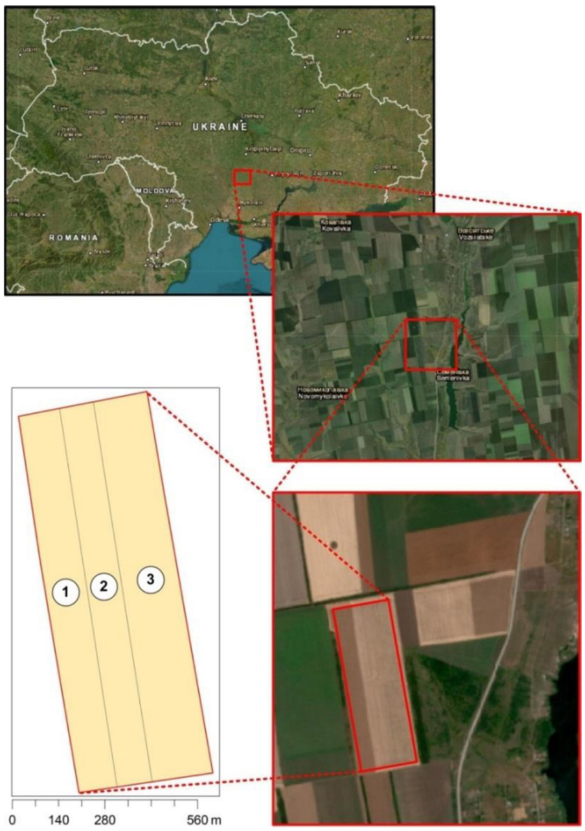


Figure 1. Location of the experimental field and the arrangement of winter wheat crops of the variety Driada 1 according to pre-crops: 1 – pea; 2 – grain crop (spring barley); 3 – sunflower

Table 1. The technology for 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 1 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 (C3-5.4) 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 a change in moisture content in the winter wheat variety Driada 1 at different stages of its growth and efficiency of moisture retention in plant leaves depending on pre-crops were established on the basis of calculation of Normalized Difference Water Index (NDWI) (Taloor et al., 2021; Medida et al., 2023):

$$\text{NDWI} = \frac{NIR - SWIR}{NIR + SWIR} \quad (1)$$

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

The NDWI values ranged from -1 to 1. The usual range for green vegetation is from -0.1 to 0.4. The values of the normalized difference vegetation index (NDVI) (Essaadia et al. 2022, Beyer et al. 2023) were calculated by the formula:

$$\text{NDVI} = \frac{NIR - Red}{NIR + Red} \quad (2)$$

where: *NIR* – the visible and near infrared band (Sentinel 2 – Band 8, 842 nm),
Red – the red band of the electromagnetic spectrum (Sentinel 2 – Band 4, 665 nm).

The NDVI values changed from 0 to 1.0. Uncovered soil of the field is characterized by the NDVI values from 0.05 to 0.10. At the beginning of sowing the NDVI values were registered at the level 0.10.

Space imagery of the spacecraft Sentinel 2 with spatial resolution of 10×10 m per pixel created in a cloudless period were used for decoding. The frequency of image processing was 10-16 days that allowed identifying NDVI and NDWI values for the macro-stages of winter wheat development, namely: sprouting (BBCH 00-09), leaf development (BBCH 10–19), tillering (BBCH 20–29), stem elongation (BBCH 30v39), booting (BBCH 41–49), ear emergence (BBCH 51v59), flowering (BBCH 61–69), milk ripeness (BBCH 71–79), wax ripeness (BBCH 81–89), grain maturation (BBCH 92v99). Correspondence of each NDWI and NDVI value to a certain macro-stage allows analyzing the formation of plant water balance and the development of winter wheat crops with regard to pre-crops.

In order to visualize cartograms of spatio-temporal distribution of the NDWI values and significance of interpretation of water index within individual plots and characteristics of heterogeneity of winter wheat growth, we interpolated values obtained on the basis of decoding satellite imagery of the spacecraft Sentinel 2. Interpolation was carried out using the method of geo-statistical analysis of the radial basis function (Chen et al., 2023; Pichura et al., 2023). This deterministic method ensured accuracy of measuring changes in the NDWI values with retaining the incoming raster data.

Space imagery processing, cartogram creation and spatio-temporal analysis were performed using the licensed program product ArcGis 10.6.

RESULTS AND DISCUSSION

Climate characteristics in the vegetative period of winter wheat in the experimental field

Zonal conditions of the research territory are characterized by medium-dry natural-climatic conditions. The mean air temperature (T, °C) of the vegetative period of the winter wheat variety Driada 1 equaled 11.4°C (Fig. 2a), the standard deviation was 8.4°C, the variance level was 74.8%. A considerable level of variance of the air temperature is characterized by seasonal fluctuations. The total precipitation (P, mm) in the vegetative period of winter wheat equaled 303 mm (Fig. 2*b*), the standard deviation – 14.1°C, the variance level – 4.7%. The autumn period 2021 of the crop growth was characterized by a sufficient moisture level and moderate air temperature regime for the Steppe zone. The total precipitation was 125 mm, the average monthly air temperature ranged 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 a high emergence rate and active photosynthetic processes of plant development before the beginning of winter dormancy.

The winter period was characterized by mild climatic conditions with the average monthly temperatures of 1.0–4.4°C and a sufficient moisture level, the total precipitation equaled 85 mm. In the second half of December 2021 and in January 2022, there was a high level of cloudiness above the research territory within 85–100%. The period was characterized by a relatively high

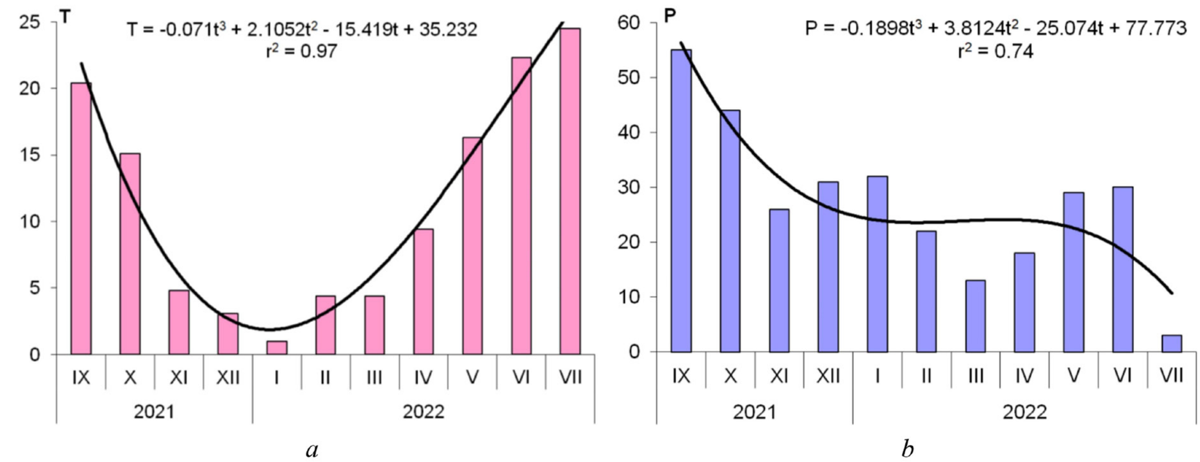


Figure 2. Climatic conditions of the vegetative period of winter wheat (2021–2022): a – average monthly temperature (T, °C); *b* – precipitation (P, mm)

level of atmospheric moisture supply, in December the total precipitation was 31 mm, in January – 32 mm. Mild temperature regime and sufficient moisture supply created favorable conditions for winter dormancy of winter wheat.

The vegetative stage of winter wheat in the spring-summer period was characterized by typical conditions of the Steppe zone. In particular, the average monthly air temperature in March was 4.4°C, the amount of precipitation was small (13 mm). The renewal of winter wheat vegetation started in the second half of March under growing degree days +5°C. April 2022 was characterized by moderate temperature +9.4°C, and the total precipitation of 18 mm, that caused a reduction in activeness of photosynthetic processes and chlorophyll production in plants at the macro-stage BBCH 30–36. May was characterized by favorable climatic conditions for winter wheat vegetation: the average air temperature was 16.3°C, the total productive precipitation equaled 29 mm. In particular, there were relatively favorable conditions for plant vegetation in June, the average monthly temperature being 22.3°C, the total productive precipitation being 30 mm. The grain crops were harvested on July 7, 2022. The first decade of July was characterized by high temperatures and a lack of precipitation.

Examination of vegetative formation of water balance in winter wheat crops

The level of crop productivity mainly depends on soil moisture content, which is necessary for seed germination and plant rooting, absorption of nutrients by plants and appropriate functioning during the vegetation period. In order to maintain the potential of productivity under conditions of a drier climate, soil tillage and a pre-crop play a key role in accumulating and retaining moisture and in creating optimal conditions for growth and development of the root system.

Under global warming, a fall in the amount or precipitation, application of conventional soil tillage and a lack of a balanced crop rotation are the reasons for significant losses of soil moisture, a deterioration in plant growth and agrocenosis productivity. Therefore, optimization of agrotechnological methods contributes to better moisture accumulation and appropriate consumption by plants, and reduces the level of unproductive losses because of evaporation. Calculation of the NDWI values (Fig. 3, 4) by means of decoded satellite images allows establishing regularities of vegetative formation of water balance in winter wheat crops depending on a pre-crop, specificity of the formation of a field micro-climate and plant development according to the unified BBCH scale, calculating spatial differentiation of plant water consumption and retention of productive moisture supply in soils.

At the beginning of sowing the winter wheat variety Driada 1 (BBCH 00) productive moisture reserves in the soil layer of 0–30 cm in the experimental field ranged from 14.5 to 24.3 mm, and it fluctuated between 55.4 and 92.4 mm in a meter soil layer. On October 6, 2021 (Fig. 3) at the beginning winter wheat sprouting (the macro-stage BBCH 09), the NDWI values ranged from -0.38 to -0.24 (Fig. 3, Fig. 5). At this time the emergence rate depended on moisture accumulated in the top soil of 0-10 cm. The period of autumn vegetation at the macro-stage of leaf development (BBCH 10–19) and tillering (BBCH 20-29) depends on a pre-crop. On Plot 1 there were favorable conditions for autumn plant development, the NDWI value at the macro-stage BBCH 10-19 increased from -0.35 to -0.28 (from October 7 to October 27, 2021). The satellite image dated October 26, 2021 shows accelerated process of moisture accumulation in plants on Plot 1 and in the north-eastern part of Plot 3, that is determined by the relief of the plot. Due to an insufficient level of moisture content that determines extreme conditions of agriculture in the Steppe zone, the macro-stage of autumn tillering had lasted in the experimental field by the time of formation of the fourth tiller (BBCH 20–24). During this period, on Plot 1, there was a relatively high level of water balance in winter wheat crops, the NDWI values over the period of tillering increased from -0.28 to -0.08; the maximum value at the end of the macro-stage of autumn tillering equaled 0.11, autumn vegetation ceased that was confirmed by the NDVI values and plants started going dormant.

On Plot 2 there was suppression in vegetation that prolonged the duration of the macro-stage of leaf development (BBCH 10–19) in comparison with the intensity of winter wheat development on Plot 1. The period of plant vegetation at the macro-stage BBCH 10–19 lasted 30 days (October 7–November 7, 2021). It was determined by a low level of accumulated water in leaves, a low level of photosynthetic processes and leaf surface area. The NDWI values at the stage of leaf development ranged from -0.34 to -0.26 (Fig. 3, Fig.

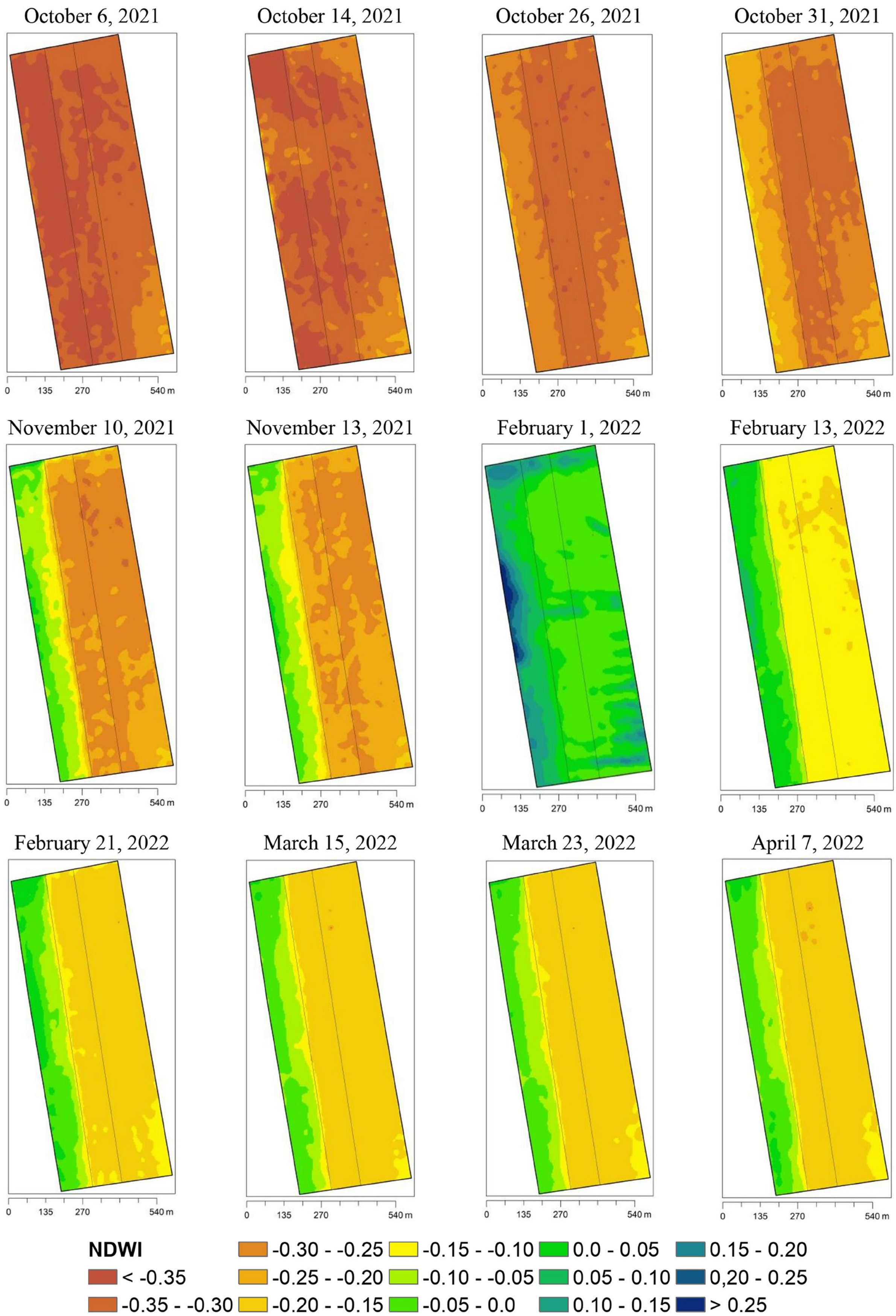


Figure 3. Seasonal differentiation of the NDWI values of the winter wheat variety Driada 1 in the experimental field at the macro-stages BBCH 00–30

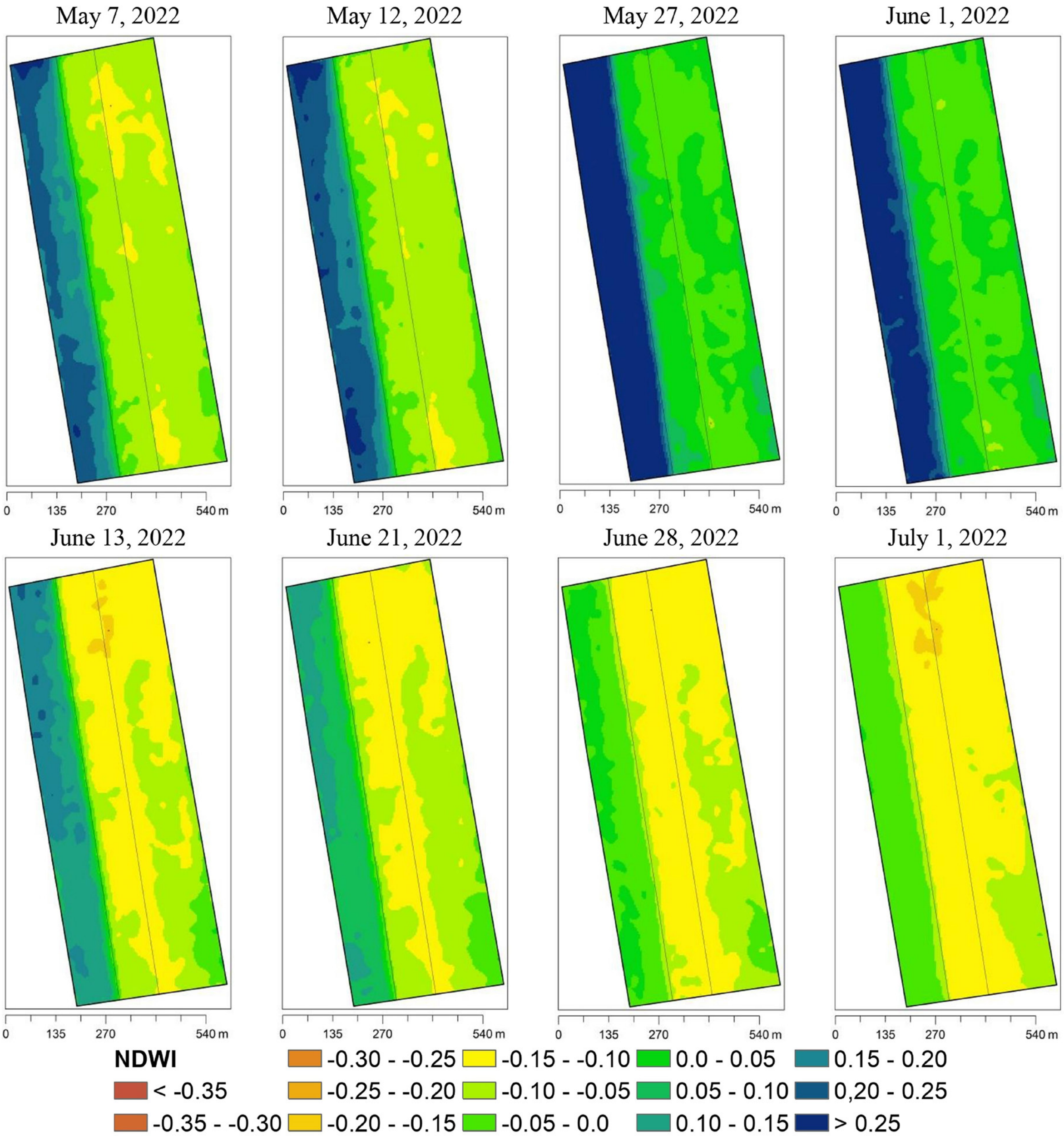


Figure 4. Seasonal differentiation of the NDWI values of the winter wheat variety Driada 1 in the experimental field at the macro-stages BBCH 31–99

5*b*). Plants on Plot 2 started going dormant at the macro-stage BBCH 21, the NDWI value ranged from -0.28 to -0.09.

On Plot 3 there was suppression in winter wheat vegetation, moisture deficit in leaves and slower metabolic chemical reactions in plants. It caused an increase in the duration of the period of autumn vegetation at the macro-stage of leaf development and the beginning of winter dormancy at the macro-stage BBCH 18. The NDWI value ranged from -0.29 to -0.18 (Fig. 3, Fig. 5*c*).

In December, 2021 and January, 2022 there was a high level of cloudiness above the experimental field that did not allow calculating the NDWI values. Therefore, the data of Mykolaiv land meteorological station were used for the research that allowed establishing a high level of moisture supply and temperature values above zero that created favorable conditions for winter wheat wintering. At the beginning of February there was a sharp increase in the NDWI values on the experimental plots, that was evident in changes in the index values from -0.06 to 0.30. High NDWI values from 0.16 to 0.30 were registered on the plots covered with snow.

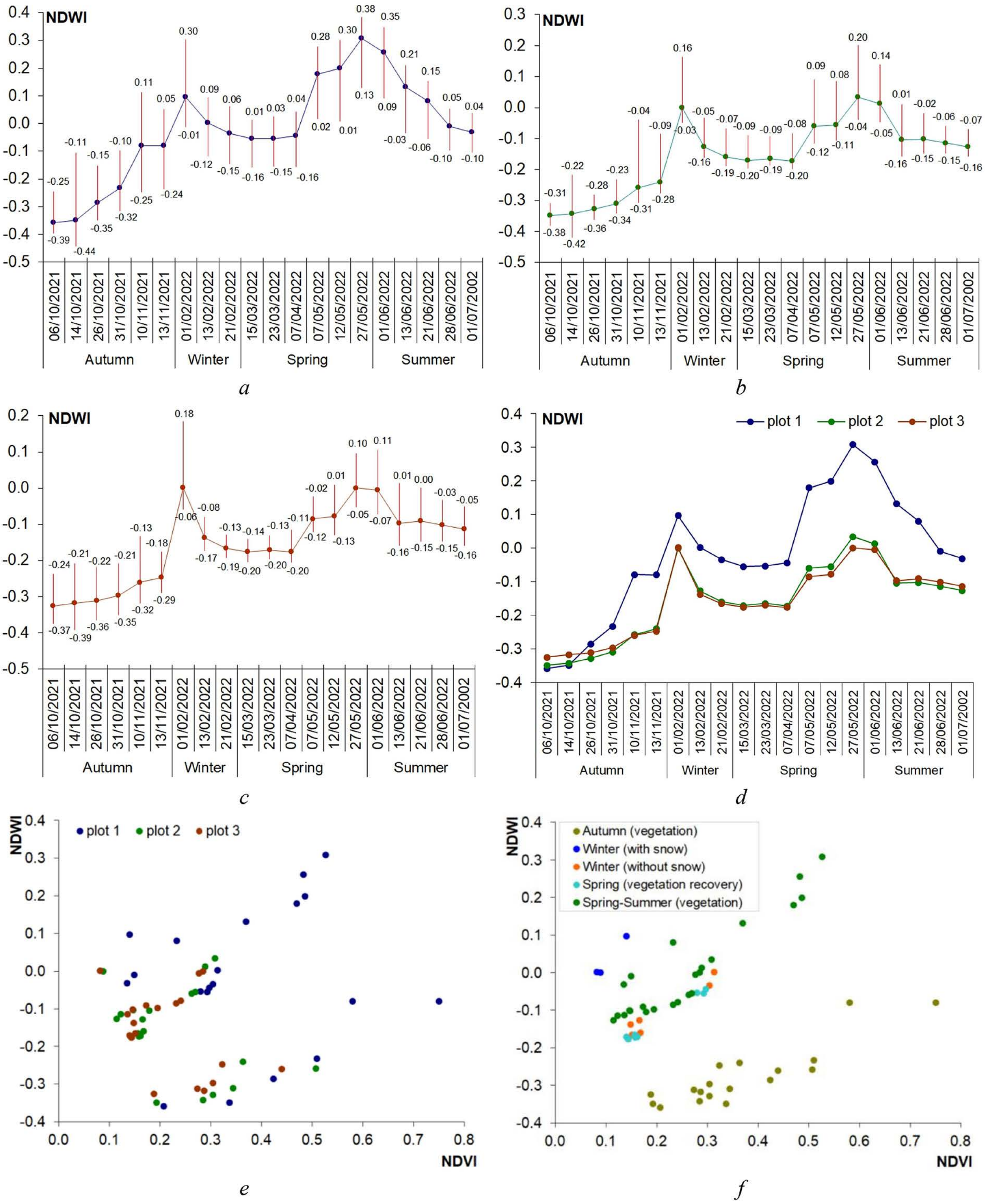


Figure 5. Seasonal distribution of the NDWI of the winter wheat variety Driada 1: *a* – Plot 1 (pea as e pre-crop); *b* – Plot 2 (a grain crop as a pre-crop); *c* – Plot 3 (sunflower as a pre-crop); *d* – mean NDWI values; *e* – differentiation of the NDWI values depending on the NDVI of winter wheat according to pre-crops; *f* – differentiation of the NDWI values depending on the NDVI values of winter wheat in each season and phenological stages of development

From February 13 to February 21, 2022 the satellite images did not register any snow cover that allowed performing accurate calculations of the NDWI of moisture retention in plant leaves in winter. It was established that a pre-crop has a considerable impact on the formation of water balance in winter wheat crops and stress-resistance to changes in winter temperatures. The

NDWI values on Plot 1 ranged from -0.15 to 0.09, on Plot 2 – from -0.19 to -0.05, on Plot 3 – from -0.19 to -0.08.

The renewal of spring vegetation of winter wheat started on March 15, 2022 and lasted till April 7, 2022, the NDWI values ranged from -0.16 to 0.03 on Plot 1(Fig. 3, Fig. 5*a*), from -0.20 to -0.09 on Plot 2 (Fig. 3, Fig. 5*b*), from -0.20 to -0.13 on Plot 3 (Fig. 3, Fig. 5*b*). The level of productive moisture fluctuated between 90.0 and 165.6 mm in the soil layer of 0-100 cm at the time of vegetation renewal. It is necessary to highlight that the periods of autumn and spring tillering and the beginning of booting BBCH 30 are very important for the formation of productive stems, ear elements and crop yields. During this stage, elongation and segmentation of the growing-point occur (vegetative cone), the formation of the ear rachis and spikelets in it continues. It is an indicator of transition from a vegetative to a generative stage of grain crop development. Therefore, the level of accumulated water in leaves at the stage BBCH 30 is an indicator of productive transition from a vegetative to a generative stage of grain crop development.

On April 7, 2022 the highest level of water in winter wheat leaves was registered on Plot 1 (Fig. 4, Fig. 5d), that created better initial conditions for increasing plant photosynthetic surface, the NDWI values being from -0.16 to 0.04 (Fig. 5a). Worse conditions were observed in the plants on Plot 2 with the NDWI values ranging from -0.20 to -0.08 (Fig. 5b), and Plot 3, the NDWI values being from -0.20 to -0.11 (Fig. 5c).

At the beginning of the stage of booting (the macro-stage BBCH 30–34), the formation of flowers in ears and active growth of the ear occur, that is a crucial period of growth and development of grain crops. At this time, agro-technological practices contribute to an increase in the number of viable productive shoots which prevent dieback of productive shoots, have a positive effect on individual plant productivity and optimal plant density, protect crops from diseases and pests at the time of booting, resulting in an increase in the ear productivity of grain crops.

An important agro-technological task is to protect grain crop leaves with chemical plant protection products, since leaf diseases are the reason for a reduction in moisture in plants, in photosynthetic surface area during vegetation that causes an earlier cessation of photosynthetic processes, a fall in activeness of chlorophyll production and a decline in crop productivity. Therefore, effective absorption of photosynthetic radiation and active growth of grain crop biomass starts with the emergence of the third leaf (BBCH 32) and lasts till the completion of milk ripeness (BBCH 79). In this period, genetic potential of winter wheat is realized. It also depends on effectiveness of agro-technological practices aimed at protection of plants against diseases and pests, plant feeding schedules and moisture retention. In particular, the state of productive shoots affecting productivity of plant photosynthetic surface is important at the macro-stages of stem elongation (BBCH 30–39) and booting (BBCH 41–49). It was established that after heading (BBCH 37–39), in the flag leaf (BBCH 31–33) and in the ear (BBCH 59), reserve substances, which are further transported and accumulated in kernel endosperm, are synthesized. The weight of a grain and the weight of 1000 grains depend on efficiency of this physiological process. Formation of 45% of the total grain weight is maintained by assimilates emerging in the flag leaf. The first, second, third and fourth leaves form 35% of the grain, the other 20% is formed from accumulated assimilates and synthesized in the ear.

In the period of the flag leaf formation, on May 7, 2022 (Fig. 4, Fig. 5), the NDWI values on Plot 1 ranged from 0.02 to 0.28, on Plot 2 – from -0.12 to 0.09, on Plot 3 – from -0.12 to -0.02. It was established that water balance in winter wheat crops on Plot 1 is 3.0–4.0 times higher than the corresponding value on Plots 2 and 3 in the period of the flag leaf formation. It determined an increase in assimilates coming to the ear on Plot 1 – 1.8–2.0 times and the formation of high ear productivity with pea as a pre-crop. At the macro-stage of booting BBCH 41-49, there was a tendency for an increase in the NDWI and there were favorable conditions for moisture accumulation on Plot 1. The period of ear emergence (BBCH 51–59) and synthesis of assimilates in the ear is an important macro-stage. Maximum growth of plant photosynthetic surface was registered in this period. The maximum water level in leaves, activeness of photosynthetic processes and chlorophyll production of winter wheat crops were registered on Plot 1, the NDWI value fluctuated between 0.13 and 0.38 on May 27, 2022. Lower NDWI values were registered on Plot 2: from -0.04 to 0.20 and on Plot 3: from -0.05 to 0.10. At the end of the macro-stages of ear emergence and the beginning of flowering (BBCH

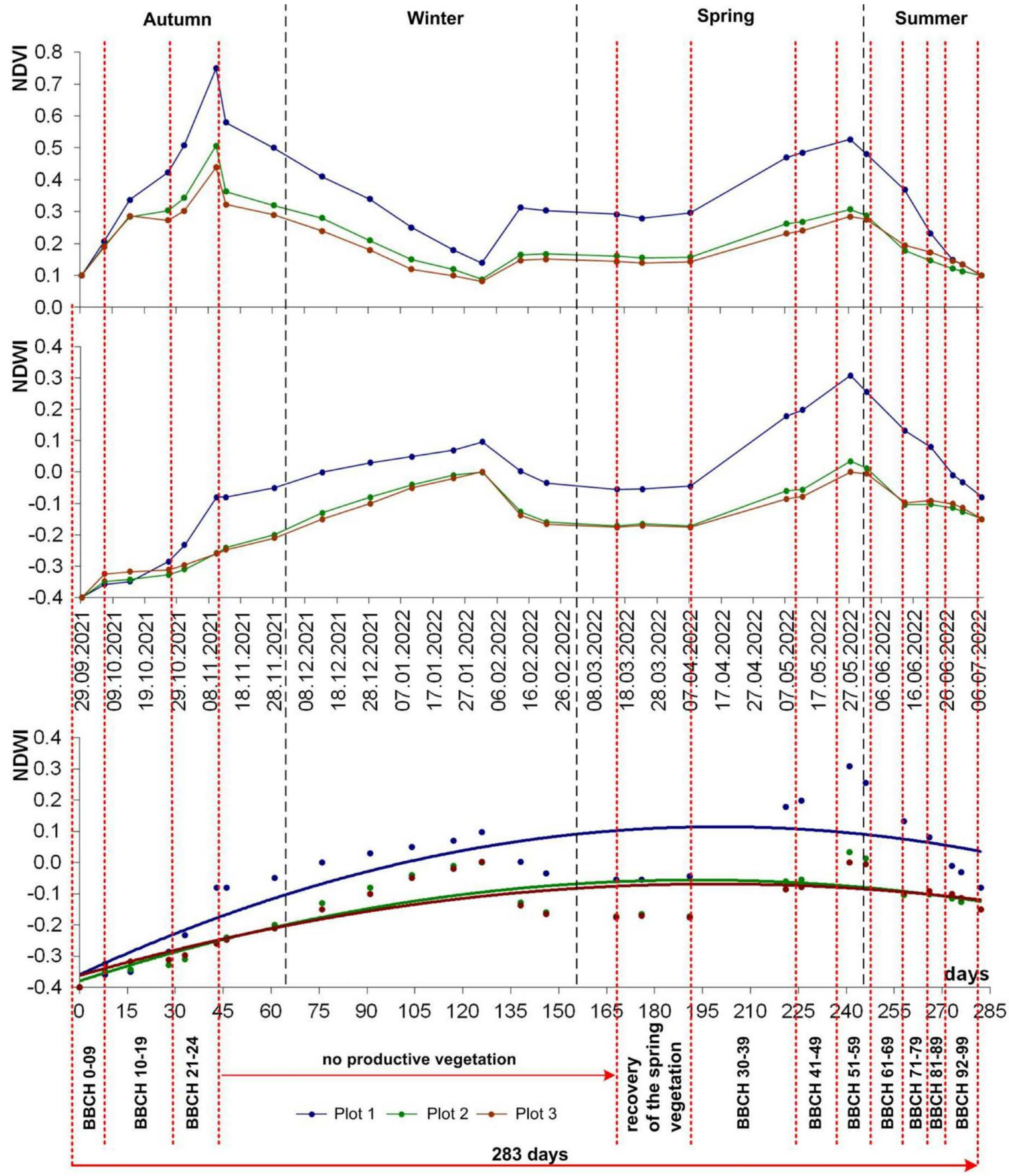
61–69), there was a reduction in moisture content in plants and a decline in photosynthetic activeness, the NDWI values on Plot 1 ranged from 0.09 to 0.35, on Plot 2 – from -0.05 to 0.14, on Plot 3 – from -0.07 to 0.11. Flowering is an important stage of organogenesis, when there occurs transition from a generative stage of plant development to a reproductive stage, marked by pollination of flowers in spikelets and the beginning of the process of kernel formation. At the macro-stage BBCH 51-61 there was a maximum value of water accumulation in plants for the entire period of vegetation which is an indicator of possible winter wheat productivity. It was established that the NDWI value is 8.5-9.0 times higher than the corresponding value on Plots 2 and 3 at the peak of water balance formation in winter wheat on Plot 1 with pea as a pre-crop. It confirms favorable micro-climatic conditions of moisture supply, an increase in stress-resistance to changes in the temperature regime, a reduction in the level of moisture evaporation from soil surface, retention of productive moisture reserves in soils for growing subsequent crops.

During the first weeks after flowering, kernels emerge in the ear that lasts till the end of the micro-stage of milk ripeness (BBCH 79). 50% of organic matter is synthesized and comes to kernels in this period, therefore, moisture retention being a factor of prolongation of photosynthetic activeness and maximum maintenance of assimilating leaf surface, is an indispensable condition for obtaining high yields. These processes are possible due to 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 NDWI values on Plot 1 considerably excessed the corresponding value on Plots 2 and 3 (Fig. 4, Fig. 5), that is an evidence of favorable conditions for grain formation. A further decline in water balance in winter wheat crops is an indicator of cessation of the process of plant absorption of photosynthetic radiation and the beginning of ripening. On July 1, 2022, at the macro-stage BBCH 92-99, the NDWI value ranged from -0.16 to 0.04. The state of crops at the micro-stage BBCH 93 “Grain loosening in daytime” is an indicator of the beginning of harvesting. Crops were harvested on July 7, 2022. It was established that the average productivity of the winter wheat variety Driada 1 equals: on Plot 1 – 4.65 t/ha, on Plot 2 – 3.24 t/ha, on Plot 3 – 2.98 t/ha.

Previous research (Pichura et al., 2023) found regularities of the impact of pre-crops on winter wheat vegetation on the basis of calculation of the NDVI by the unified BBCH scale. It allowed establishing regularities of the NDWI differentiation depending on the NDVI of winter wheat according to a pre-crop (Fig. 5*e*), seasons and phenological stages of development (Fig. 5*f*).

It was established that a pre-crop affects growth of a subsequent crop, the rate and amount of water accumulated in leaves, photosynthesis intensity, leaf surface area, the metabolic rate and the formation of winter wheat productivity. It was established that the best vegetation, formation of morphological properties and water balance of leaves were observed in the crops with pea as a pre-crop at all the stages of plant development (Fig. 5*e*). For instance, in the vegetation period in autumn, at the macro-stage (BBCH 10-24), the average NDVI value fluctuated between 0.21 and 0.75 and the NDWI value ranged from -0.36 to -0.08 on Plot 1; the NDVI value fluctuated between 0.19 and 0.51 and the NDWI value ranged from -0.35 to -0.24 on Plot 2; the NDVI value fluctuated between 0.19 and 0.44 and the NDWI value ranged from -0.32 to -0.25 on Plot 3. In the period of winter dormancy, in the period without snow the situation was the following: the NDVI value equaled 0.30-0.31 and the NDWI value ranged from -0.03 to 0.0 on Plot 1; the NDVI value equaled 0.16 and the NDWI value fluctuated between -0.17 and -0.13 on Plot 2; the NDVI value equaled 0.15 and the NDWI value ranged from -0.17 to -0.14 on Plot 3. At the renewal of spring vegetation, the NDVI value ranged from 0.27 to 0.29 and the NDWI value fluctuated between -0.06 and -0.05 on Plot 1; the NDVI value equaled 0.16 and the NDWI was -0.17 on Plot 2; the NDVI value equaled 0.14 and the NDWI value was at the level -0.18 on Plot 3. In the spring-summer period of vegetation, at the macro-stage (BBCH 30-93), the average NDVI value fluctuated between 0.29 and 0.53 and the NDWI value ranged from -0.05 to 0.31 on Plot 1; the NDVI value fluctuated between 0.11 and 0.31 and the NDWI value ranged from -0.11 to 0.03 on Plot 2; the NDVI value fluctuated between 0.14 and 0.28 and the NDWI value ranged from -0.10 to 0.0 on Plot 3. The research allowed establishing seasonal regularities of water accumulation in winter wheat plants (Fig. 5*f*), in particular, in the autumn period of vegetation, at the macro-stage (BBCH 10–24), the NDWI value fluctuated between -0.36 and -0.08, in the period of winter dormancy with snow cover, it ranged from 0 to 0.10 and without snow cover – from -0.17 to 0, in the period of the renewal of spring vegetation it ranged from -0.18 to -0.05, in the spring-summer period of vegetation, at the macro-stage (BBCH 30–93), it fluctuated between -0.11 and 0.31.

On the basis of the results obtained by means of spatio-temporal seasonal decoding of satellite imagery and calculations of the NDWI values, it was established that the formation of water balance of winter wheat agrocenosis on Plot 1 with pea as a pre-crop occurred 3.0–9.0 times more actively than on Plots 2 and 3 (Fig. 6). In



Pea as a pre-crop: $NDWI = 0.1 \cdot 10^{-4} t^2 + 0.0047t - 0.3592 \quad r^2 = 0.70$

Spring barley as a pre-cop: $NDWI = 0.9 \cdot 10^{-5} t^2 + 0.0033t - 0.3798 \quad r^2 = 0.72$

Sunflower as a pre-crop: $NDWI = 0.7 \cdot 10^{-5} t^2 + 0.0029t - 0.3623 \quad r^2 = 0.71$

Figure 6. Changes in the NDVI and the NDWI values of winter wheat according to the unified BBCH scale

particular, vegetation of winter wheat plants by the NDVI on Plot 1 with pea as a pre-crop occurred 1.6 times more actively than on Plot 2 (a grain crop (spring barley) as a pre-crop), and 1.7 times more actively than on Plot 3 (sunflower as a pre-crop). As a result, there was an increase in winter wheat productivity on Plot 1 in comparison with productivity on Plots 2 and 3 – 1.43 and 1.56 times, respectively (Fig. 7). It was found that the rate of increase in moisture reserves in plant leaves at the macro-stages BBCH 10–61 on Plot 1 is 1.54 and 1.82 times higher than the corresponding value on Plots 2 and 3. The research established a positive effect of a pre-crop on winter wheat vegetation, water balance, productivity of plant photosynthetic surface, activeness of photosynthetic processes, chlorophyll production that manifests itself in an increase in productivity of agricultural crops.

The research allowed drawing a conclusion about environmental and economic benefits of crop rotations, the capability to reduce the use of

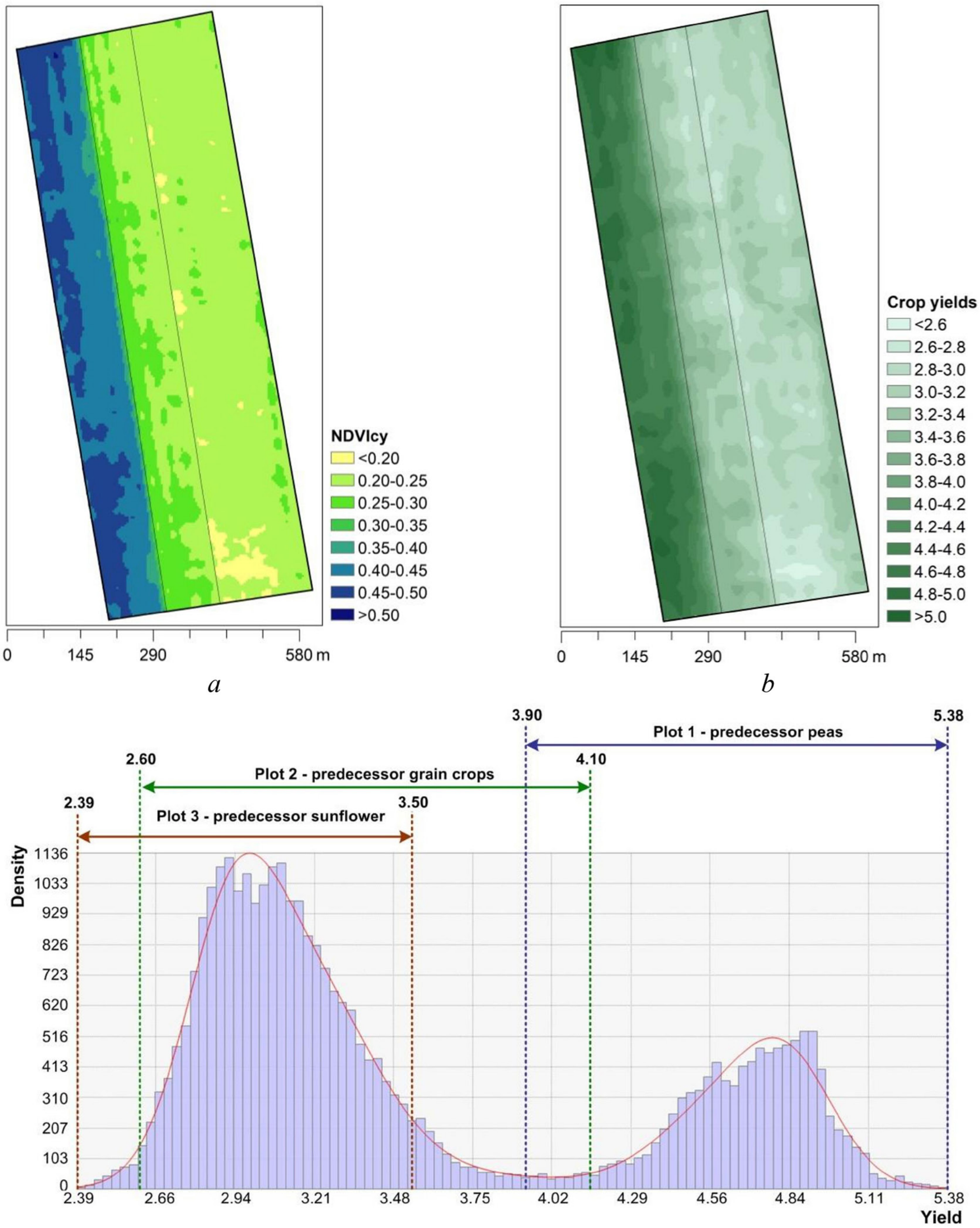


Figure 7. Yield formation of the winter wheat variety Driada 1: *a* – cartograms of distribution of the generalized NDVI data; *b* – cartogram of yield distribution; *c* – histogram of yield distribution

productive moisture reserves in soils and increase their resistance in the zone of moisture deficit and extreme agriculture. First of all, retention of moisture in soils enhances their biological condition, intensifies humification and restores fertility, improves physical-chemical properties, reduces the impact of erosion processes, creates favorable initial conditions for growing subsequent crops. Therefore, determination of the level of productive moisture in soils at the beginning and at the end of the vegetation period and calculation of the coefficient of plant water consumption depending on a pre-crop are important factors of forecasting productivity of agricultural crops.

At the beginning of winter wheat planting, productive moisture reserves in the soil layer of 0–30 cm in the experimental field ranged from 14.5 to 24.3 mm (Fig. 8*a*). About 70% of the field area was characterized by a sufficient level of moisture content in the upper layer (21–30 mm of productive moisture reserves), 30% of the field area was characterized by an insufficient

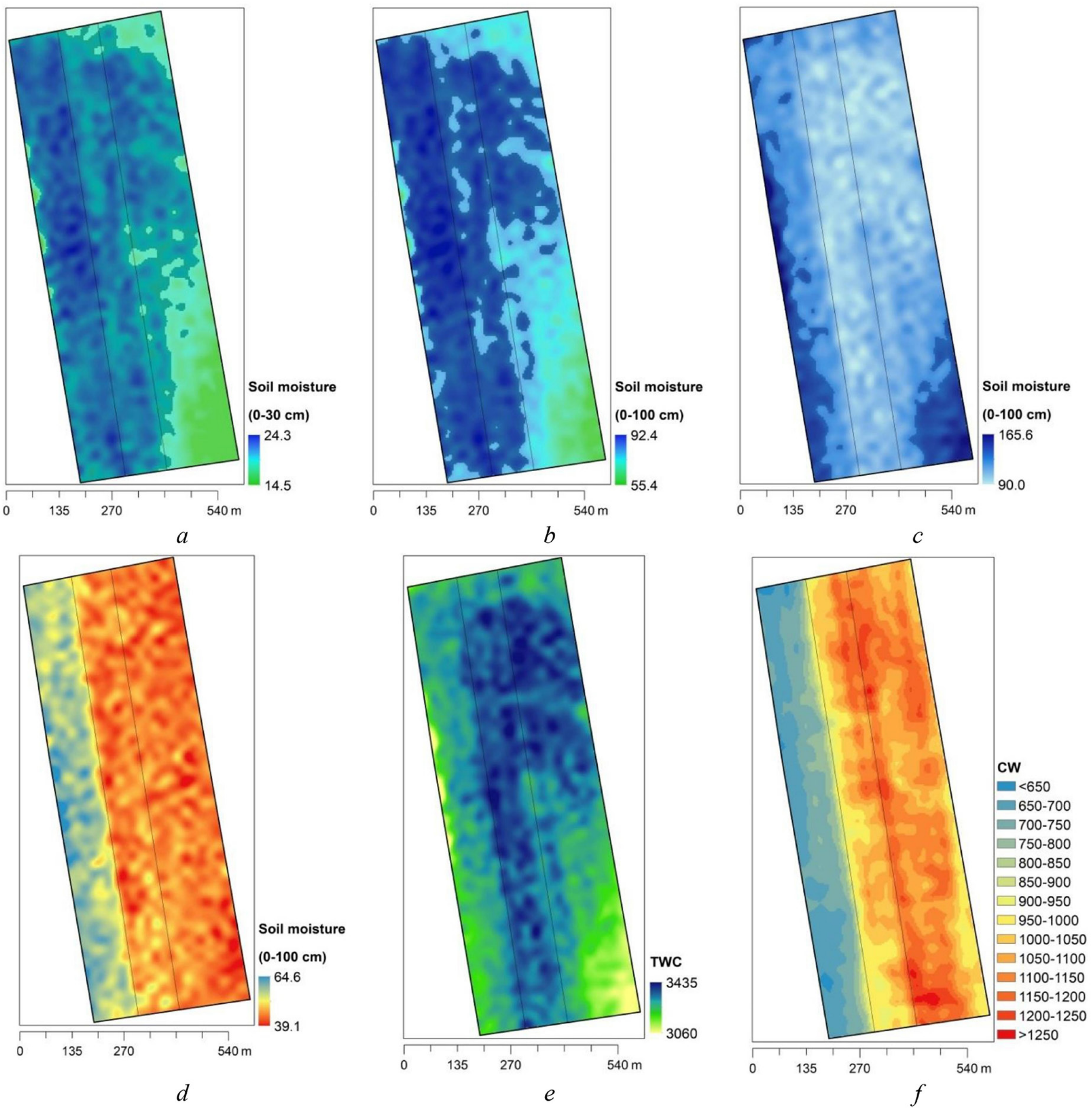


Figure 8. Differentiation of productive moisture reserves (mm) in the soils of the experimental field and water consumption (m^3/t) by winter wheat plants: a – moisture at the beginning of sowing in the soil layer of 0–30 cm, mm; b – moisture at the beginning of sowing in the soil layer of 0–100 cm, mm; c – moisture at the time of the renewal of vegetation in the soil layer of 0-100 cm, mm; d – soil moisture at the end of vegetation in the soil layer of 0-100 cm, mm; e – total water consumption (TWC) in the vegetation period, m^3/t; f – water consumption (CW) per 1 t of yield, m^3/t

level of moisture content (11–20 mm of productive moisture reserves).

It was established that productive moisture reserves in a meter soil layer equaled 55.4–92.4 mm (Fig. 8*b*). About 57% of the field area was characterized by a sufficient level of moisture content in a meter soil layer (81–120 mm of productive moisture reserves), 43% of the field area was characterized by an insufficient level of moisture content (51–80 mm of productive moisture reserves). The largest part of the filed with an insufficient level of moisture content at the beginning of winter wheat planting is located in slightly-eroded soils with low contents of clay.

The examined period of winter dormancy of winter wheat was characterized by mild climatic conditions and a high level of atmospheric moisture supply for the Steppe zone of Ukraine. The total precipitation in winter equaled 85 mm that contributed to additional accumulation of moisture and maintained sufficient (81–120 mm of productive moisture reserves) and optimal (more than 120 mm of productive moisture reserves) levels of soil moisture in the layer of 0–100 cm (Fig. 8c) and sufficient climate energy at the renewal of spring vegetation of winter wheat. Productive moisture reserves under the crops at the end of vegetation in the soil layer of 0-100 cm (Fig. 8d) ranged from 39.1 to 64.6 mm, in particular: on Plot 1 – from 44.0 to 64.6 mm; on Plot 2 – from 42.0 to 52.7 mm; on Plot 3 – from 39.1 to 50.3 mm. It was found that Plot 1 with pea as a pre-crop had productive moisture reserves higher by 18% and 20% at the end of vegetation in a meter soil layer than on Plots 2 and 3, respectively. It was established that the total water consumption of winter wheat in the vegetation period ranged from 3060 to 3435 m^3 (Fig. 8e). In particular, water consumption for the formation of a ton of wheat grain (Fig. 8f) on Plot 1 fluctuated between 630 and 975 m^3/t, on Plot 2 – from 860 to 1226 m^3/t, on Plot 3 – from 925 to1286 m^3/t. In other words, on Plot 1 with pea as a pre-crop, water consumption for the formation of a ton of winter wheat grain is less by 30.5% and 34.3% than on Plots 2 and 3, respectively.

Statistical characteristics of spatio-vegetative regularities of the impact of pre-crops on the formation of winter wheat productivity and soil moisture retention are given in Table 2.

The studies by N.V. Beznitska (2017), Yang et al. (2023) and Asmamaw et al. (2023) emphasize that providing plants with moisture at the beginning of sowing and during the vegetation period by means of additional irrigation is an important factor in obtaining optimal yields in dry regions. The scientific works by Mu et al. (2023), Senbeta and Worku (2023) show that an increase in agricultural crop yields on irrigated lands ranges from 11.5% to 33.4% in medium-wet years in the zone of moisture deficit. Yields of the basic field crops rise 2.5–3.0 times in dry years on irrigated lands. In particular, an increase in yields is accompanied by a rise in nutrient depletion. Therefore, optimization of water and fertilizers is important in irrigation, since it has a crucial impact on obtaining high yields and efficiency of using resources (Li et al., 2019). However, the current conditions of irrigated agriculture in the Steppe zone of Ukraine are complicated by military operations, destruction

Table 2. Generalization of statistical characteristics of the parameters of growing the winter wheat variety Driada 1 depending on pre-crops

Parameters	Pre-crops		
	Plot 1 – pea	Plot 2 – spring barley	Plot 3 – sunflower
	$\frac{aver \pm \sigma}{min \rightarrow max}$		
NDVI	$\frac{0.36 \pm 0.16}{0.05 \rightarrow 0.90}$	$\frac{0.23 \pm 0.10}{0.03 \rightarrow 0.69}$	$\frac{0.21 \pm 0.09}{0.00 \rightarrow 0.64}$
NDWI	$\frac{-0.02 \pm 0.19}{-0.44 \rightarrow 0.38}$	$\frac{-0.16 \pm 0.12}{-0.42 \rightarrow 0.20}$	$\frac{-0.16 \pm 0.11}{-0.39 \rightarrow 0.18}$
Yield, t/ha	$\frac{4.65 \pm 0.31}{3.90 \rightarrow 5.38}$	$\frac{3.24 \pm 0.26}{2.60 \rightarrow 4.10}$	$\frac{2.98 \pm 0.20}{2.39 \rightarrow 3.50}$
Water consumption per 1 t of yield, m^3/t	$\frac{800 \pm 53.3}{630 \rightarrow 975}$	$\frac{1050 \pm 84.3}{860 \rightarrow 1226}$	$\frac{1100 \pm 74.2}{925 \rightarrow 1286}$
Soil moisture at the end of vegetation (0–100 cm), mm	$\frac{54.3 \pm 3.6}{44.0 \rightarrow 64.6}$	$\frac{47.3 \pm 3.8}{42.0 \rightarrow 52.7}$	$\frac{44.7 \pm 3.0}{39.1 \rightarrow 50.3}$

of the Kakhovka dam and irrigation systems, damage to soil cover and partial occupation of the Ukraine's territory by russian aggressors. Therefore, the issue of ensuring food security and Ukraine's export potential due to implementation of efficient agro-technological methods for increasing crop productivity in the zone of moisture deficit is topical. Such practices should by introduced on the basis of substantiation of balanced application of crop rotations (Berzsenyi et al., 2000; Bruns 2012, Li et al., 2019). It was proved that efficiency of using legume crops in the structure of crop rotations is not less than 25.0% (Neugschwandtner and Kaul 2015; Khakbazan et al., 2019; Fang et al., 2023). Therefore, approaches to application of a series of satellite images for thorough examination and identification of spatio-temporal regularities in vegetation and formation of agrocenoses productivity, exemplified by winter wheat depending on using different pre-crops, namely, pea, spring barley and sunflower, were further developed and improved taking into consideration the available scientific studies. Analysis of scientific literature and findings of our research allowed confirming scientific and practical efficiency of using legume crops in crop rotations for increasing productivity of after-crops and retaining soil moisture, the value of applying modern technologies of remote sensing for improving the monitoring of areas under crops, managing and determining efficiency of agro-technological methods, for increasing reliability of forecasting agrocenosis productivity within a particular field and on the farmlands of individual agricultural commodity producers. It was established that using pea in crop rotations in the zone of agricultural risks is an efficient agricultural practice since it contributes to vegetation of after-crops, formation of good morphological characteristics of plants and water balance, an increase in crop resistance to stressful climatic conditions, a rise in agrocenosis productivity and effective moisture supply in soils of farmlands. In particular, saturation of crop rotations with pea has ecological and economic effects which manifest themselves in an increase in agrocenocis productivity, a reduction in the rates of nitrogen fertilizers with a corresponding increase in profitability of agricultural production. The obtained results will allow land-users to adjust the system of growing agricultural crops in the zone of moisture deficit and agricultural risks to ensure production profitability.

CONCLUSIONS

The study examined spatio-temporal processes of vegetation and the formation of water balance in winter wheat agrocenosis depending on a pre-crop according to the unified BBCH scale under non-irrigated conditions of the Steppe zone of Ukraine. It was found that the formation of water balance in winter wheat agrocenosis on Plot 1 with pea as a pre-crop according to seasonal-phenological stages of plant vegetation occurs 3.0–9.0 times more actively than on Plot 2 with a grain crop (spring barley) as a pre-crop and on Plot 3 with sunflower as a pre-crop. In particular, plant vegetation of winter wheat crops on Plot 1 occurred 1.6 more actively than on Plot 2 and 1.7 times more actively than on Plot 3. Consequently, there was 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.

It was established that the rate of increase in moisture reserves in plant leaves at the macro-stages BBCH 10-61 on Plot 1 was 1.54 and 1.82 times higher than the corresponding value on Plots 2 and 3. It was proved that water consumption for the formation of a ton of grain with pea as a pre-crop is by 30.5% and 34.3% less than on Plots 2 and 3, respectively. It resulted in a 20% increase in productive moisture reserves at the end of vegetation in a meter soil layer on Plot 1. It was proved that using pea in crop rotations in the zone of risky farming determines nitrogen fixation in soil that improves conditions for vegetation of a subsequent crop, contributes to the formation of morphological properties and leaf water balance, an increase in the metabolic rate and plant photosynthesis, a better field micro-climate, a reduction in intensity of evaporation and use of productive moisture reserves in soil, an increase in stress-resistance of soil systems and higher productivity of agricultural crops.

The obtained research results can be used to improve methods for examining vegetation of agricultural crops, substantiating crop rotations, managing resources, developing adaptive-climatic agricultural technologies, forecasting agricultural crop productivity and profitability of economic activity of enterprises in the soil-climatic conditions of the Steppe zone of Ukraine.

Acknowledgments

This investigation was supported by the Ministry of Education and Science of Ukraine for the projects: "Agroecological substantiation of system application of multifunctional growth-regulating preparations for cultivation the main field crops in the conditions of the Steppe zone of Ukraine" (state registration 0121U109552), 2021–2023; "Ecological and Economic Substantiation of the Development of Biological Technologies of Cultivation of the Main Field Crops in The Steppe Zone under the Conditions of Climate Change" (state registration 0122U000867), 2022–2023; "Development of biological technologies for the cultivation of grain crops during the post-war reconstruction of Ukraine" (state registration 0123U101865), 2023–2024.

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