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FROM IRRIGATION STABILITY TO ARIDIFICATION: WAR-INDUCED TRANSFORMATION OF IRRIGATED AGROECOSYSTEMS IN SOUTHERN UKRAINE

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ABSTRACT

The study assesses spatio-temporal patterns of transition from irrigation stability to aridification of agricultural landscapes in Southern Ukraine due to war-induced destruction of water infrastructure and increased climate extremes. The subject of analysis is the irrigated area in the Kherson region, whose functioning depended on the Kakhovka Reservoir's resources until 2023. The research methodology is based on the integrated use of the Soil Water Index (SWI) and Terrestrial Chlorophyll Index (OTCI) from satellite observations, analysis of temperature and hydrothermal indices, and assessment of yield trends between 2021 and 2025. A cascading degradation mechanism was observed: the loss of water-regulating function after the Kakhovka Dam's destruction in 2023 and the Reservoir's drainage have caused the depletion of productive soil moisture, a decline in plant photosynthetic activity, increased heat and drought stress, and a sharp drop in crop productivity. SWI trends indicated transition from largely satisfactory moisture levels in 2021 to prevalent high or critical water stress between 2024 and 2025. The synchronous decrease in the OTCI confirmed vegetation cover degradation. The index peak values decreased more than twofold, which corresponds to the transition from highly productive irrigated agrocenoses to degradation with signs of soil drought. The findings demonstrate a synergistic effect of war-induced and climate-related factors, which have created preconditions for the region's long-term aridification. The study substantiates the necessity of restoring water management and devising adaptive strategies for postwar irrigation rehabilitation as a key factor in rebuilding the bioclimatic resilience of Southern Ukraine.

Keywords: Kakhovka Reservoir; Soil Water Index (SWI); Terrestrial Chlorophyll Index (OTCI); remote sensing; hydrological transformation; heat and drought stress.

INTRODUCTION

The current challenges to the sustainable development of Ukraine's irrigated areas stem from an unprecedented combination of natural climate-related and anthropogenic

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war-induced factors. Southern Ukraine, where the main irrigated areas are concentrated, has always played a key role in ensuring the country's food security and generating its export agricultural potential. At the same time, these areas are characterized by heightened climate vulnerability, moisture deficit, and the critical dependence of agricultural production on irrigation and land reclamation infrastructure. The ongoing full-scale war, which began in 2022, has compounded existing climate risks, considerably transforming hydrological, environmental, and soil bioproductive conditions affecting the functioning of water-dependent areas (Snizhko *et al.,* 2024; Hapich *et al.,* 2024; Pichura & Potravka, 2025).

Climate change in Ukraine's steppe zone manifests in increasing air temperatures, more frequent prolonged droughts, uneven precipitation distribution, and more severe extreme weather events. This leads to progressive aridification, a decline in natural soil moisture, and the exacerbation of degradation processes such as deflation, secondary salinization, dehumidification, and desertification (Dudiak *et al.,* 2021; Lisetskii & Pichura, 2016). Under these conditions, irrigation is a key instrument in agricultural landscape adaptation to water shortages, maintaining production stability, water balance, and climate resilience in the area (Pichura *et al.,* 2023; Mekonnen & Hoekstra, 2016).

Since 1960, the Kakhovka Reservoir has been the backbone of water management and water supply in Southern Ukraine. Its surface area was 2155 km², its total volume was 18.2 km³, and its usable volume was 6.8 km³. Constructed in 1955–1958 in the Lower Dnipro area, it performed various functions in energy supply, irrigation, water supply, fisheries, recreation, and nature protection. The Reservoir provided freshwater for industry, agriculture, and a population of about 6 million. It was also the only source of water supply for the Zaporizhzhia NPP's cooling systems (Solokha *et al.,* 2023; Bonchkovskyi *et al.,* 2025; Zhukov *et al.,* 2025). The project resources were aimed at irrigating over 1 million hectares of land, including over 400 thousand hectares in the Kherson region, over 350 thousand hectares in Crimea, about 200 thousand hectares in the Zaporizhzhia region, and over 100 thousand hectares in the Mykolaiv and Dnipropetrovsk regions. Until 1990, the annual water withdrawal exceeded 12 billion m³ ³ (Romashchenko *et al.,* 2025). However, between 1990 and 2021, the actual irrigated area decreased to about 450 thousand hectares due to underfunding and the infrastructure's technical degradation (Pichura *et al.,* 2023).

Irrigation radically changed the functioning of the natural and economic environments. Between 2014 and 2021, the total annual water withdrawal from the Reservoir was 1.21–1.34 billion m³, 800–950 million m³ of which were used for agricultural purposes (Pichura *et al.,* 2023; Hapich *et al.,* 2024). Additional moisture contributed to the intensification of soil formation and hydrological processes, an increase in moisture content, and a decline in temperature stress. As a result, the bioclimatic potential of agricultural landscapes increased by 1.7 times, and crop productivity rose by 2.5 times on average, indicating the stabilizing role of irrigation in the functioning of the agricultural sector and the formation of ecosystem services in irrigated landscapes (Pichura *et al.,* 2023).

Russia's full-scale invasion in 2022 caused systemic disruptions to the operation of the water management complex, including the destruction of hydraulic structures and pumping stations, damage to water canals and energy infrastructure, soil and water pollution, minefields, and degradation of agricultural landscapes (Hapich *et al.,* 2024; Snizhko *et al.,* 2024). The destruction of the Kakhovka Dam on June 6, 2023, marked a critical phase of hydro-ecological transformation, causing the drainage of the Reservoir as the main irrigation source in Southern Ukraine. The disaster has led to a radical change in the region's hydrological regimes, the disruption of surface and groundwater balance, the loss of the capacity to accumulate freshwater resources, and the emergence of long-term risks of

secondary environmental pollution, particularly due to the mobilization of bottom sediments and their migration to the Dnipro-Buh Estuary and the Black Sea (Shumilova *et al.,* 2023; Vyshnevskyi *et al.,* 2023; Vyshnevskyi & Shevchuk, 2024; Pichura *et al.,* 2025a; Shumilova *et al.,* 2025).

The disaster's negative effects have been considerably amplified by the occupation of the Lower Dnipro's left bank, where over 80% of Ukraine's irrigated lands are located, creating additional barriers to water resource management, monitoring, and restoration of land reclamation systems. Annual land users' economic losses are estimated at over 4 million tons of grain (over 1.5 billion US dollars), undermining the country's food security and export potential and enhancing the geostrategic importance of irrigation rehabilitation in the post-war period (Snizhko *et al.,* 2024; Hapich *et al.,* 2024).

The destruction of the Kakhovka water management and irrigation complex has triggered a profound transformation of natural and economic systems in the irrigated area (Vyshnevskyi *et al.,* 2023; Vyshnevskyi & Shevchuk, 2024; Pichura *et al.,* 2025; Romashchenko *et al.,* 2025; Lisovets *et al.,* 2025; Tutova *et al.,* 2025, 2025a), warranting a scientifically substantiated assessment of the scope and mechanisms of these changes, their interactions with climate extremes, and their effects on the area's water regime and bioproductivity.

The research aims to clarify the spatio-temporal patterns of transition from irrigation stability to aridification in Southern Ukraine based on a comprehensive assessment of the aggregate effect of the war-induced destruction of the irrigation infrastructure and climate extremes on water regime, the operation of land reclamation systems, and the soil bioproductivity of irrigated agricultural lands in the Kherson region.

MATERIAL AND METHODS

Research area

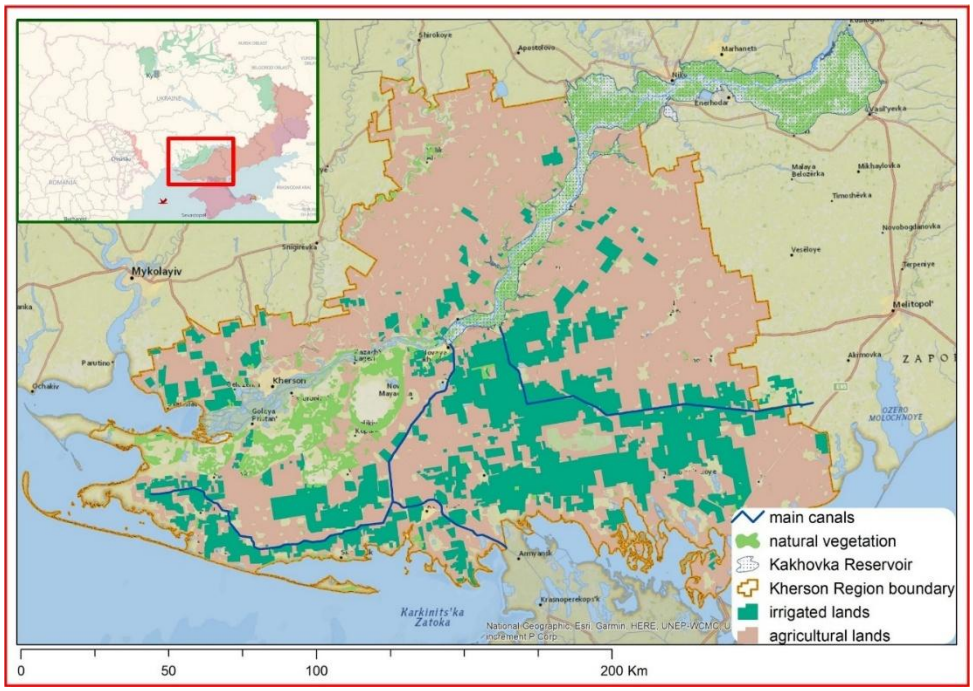
The research subject includes agricultural landscapes in the Kherson region, located in the Black Sea lowland in Southern Ukraine. The spatial framework of the study was based on the boundaries of agricultural lands, within which a historical irrigated area that had functioned before the destruction of the Kakhovka HPP in 2023 was identified (Fig. 1). The boundaries of the research area were identified based on the integration of official irrigation system maps, the boundaries of agricultural lands, and Sentinel-2 satellite imagery. Analysis of the Soil Water Index and Terrestrial Chlorophyll Index was conducted for all agricultural lands in the region. The spatio-temporal changes related to the cessation of irrigation between 2021 and 2025 were assessed separately within the historical irrigated area. Throughout the research period, the same spatial boundaries were used to ensure accurate year-over-year comparisons of the results.

The research area is located in the steppe climate zone and is characterized by high air temperatures, low precipitation, and a significant natural moisture deficit. The region's total area is 2846.1 thousand hectares, including 1,971.0 thousand hectares (69.3 %) of agricultural land, with arable land totaling 1,777.6 thousand hectares. The soil cover largely consists of low-humus southern black soils (humus content – 0.30–3.85%), which constitute 43.7 % of the total area, and dark chestnut soils (30.7%) (Pichura *et al.,* 2023; Dudiak *et al.,* 2021). The area is distinguished by a large portion of arable land and a high dependence of agricultural production on artificial irrigation.

The project area of the region's irrigated land totaled 426.4 thousand hectares, accounting for about 20 % of Ukraine's irrigated area. The actual use of irrigation systems between 2003 and 2021 ranged from 250 to 315 thousand hectares. The main irrigation systems are located

on the Dnipro's left bank, including the Kakhovka (243.1 thousand hectares), Kalanchak, and Krasnoznamianka irrigation systems (totaling 102 thousand hectares), which used the Kakhovka Reservoir as a source of water supply. Part of the Inhulets irrigation system covering an area of 18.2 thousand hectares operated on the region's right bank and used the Inhulets River's water with high mineralization. Furthermore, local irrigation systems covering an area of 22.4 thousand hectares operated in the region. The local irrigation area was 40.7 thousand hectares. In the left-bank part of the region, there were rice irrigation systems with a total area of 8.1 thousand hectares (Pichura *et al.,* 2023).

Fig. 1: Location of irrigation systems and main irrigation canals in the Kherson region



Note: The map shows the land-use structure in the Kherson region, featuring irrigated lands, natural vegetation, and agricultural lands. It also shows the network of main irrigation canals and the region's boundaries, as well as the water area of the Kakhovka Reservoir, as the key source of water supply for irrigation systems. The inset in the left corner shows the location of the research area in Ukraine.

The area is characterized by an arid steppe climate, a sum of positive temperatures exceeding 3000 °C per year, and an atmospheric moisture deficit during the growing season, which has made crop productivity critically dependent on artificial irrigation. The average annual precipitation is 300–500 mm, with its biyearly amount being critically low (<400 mm). Potential evapotranspiration is twice the amount of precipitation, which has led to natural aridification in the area (Lisetskii & Pichura, 2016; Mekonnen & Hoekstra, 2016; Pichura *et al.,* 2023).

As of February, 2026, 72.11 % of the Kherson region (the entire left-bank part) remains temporarily occupied, where about 93 % of irrigated lands, 425 settlements (65 % of their total number), and 13 administrative districts (68 % of the region's territorial structure) are located.

The main research periods

Spatio-temporal analysis was conducted between 2021 and 2025. This period covers the pre-war operation of irrigation systems (2021), the partial disruption of their functioning (2022), the time after the destruction of the Kakhovka HPP Dam (2023), the loss of irrigation, and the cessation of water supply to the main canals (2024–2025). July, as the period of maximum heat load and water stress in plants, was considered the key analytical month.

Data sources

The research used data from:

– The Kakhovka hydrological and land reclamation expedition (https://buvrnd.gov.ua/kggme.htm): the layout of the hydraulic network and irrigated lands, groundwater levels;

– The State Agency for Water Resources of Ukraine (https://www.davr.gov.ua/): the area of irrigated lands and irrigation water volumes;

– The Department of Agricultural Development and Irrigation of the Kherson Regional State Administration (https://khoda.gov.ua/oda-i-orhany-vlady/strukturni-pidrozdily/departament-rozvytku-silskoho-hospodarstva-ta-zroshennia): yield trends and the loss of crops;

– Temperature indices were analyzed using the data from the Meteostat station-based observations (https://meteostat.net/) and NOAA National Centers for Environmental Information. Global Surface Summary of the Day (GSOD – https://www.ncei.noaa.gov/), verified by the ERA5-Land (Copernicus Climate Data Store – https://cds.climate.copernicus.eu/), which contributed to continuous climate data flow and spatial data consistency: precipitation (P, mm), air temperature (T, °C), the sum of positive temperatures (ΣT>10 °C), the number of days with T_{max} >35 °C, and potential evaporation (ET_0, mm);

– Satellite imagery from Sentinel-3 OLCI L1B at the Copernicus Browser (https://browser.dataspace.copernicus.eu/) with a resolution of 270 m – to calculate the OTCI;

– Copernicus Land Monitoring Service (https://land.copernicus.eu/en/products/soil-moisture) at the Copernicus Browser with a resolution of 1 km – to calculate the Soil Water Index (SWI).

Calculation of Terrestrial Chlorophyll Index (OTCI)

To assess the condition of vegetation cover and the intensity of photosynthetic activity, the OTCI, the spectral index of chlorophyll content in the terrestrial phytomass, was used. The index was calculated based on satellite imagery from Sentinel-3 OLCI (Level-1B).

The OTCI was calculated using the formula (Dash *et al.*, 2010; Kovács *et al.*, 2024):

$$OTCI = \frac{(B12 - B11)}{(B11 - B10)} \quad (1)$$

where: B10, B11, B12 – the reflectance values of the corresponding spectral channels of the OLCI sensor: B10 (≈ 681 nm) – the red band (chlorophyll absorption); B11 (≈ 709 nm) – the "red-edge" band; B12 (≈ 753 nm) – the near infrared band.

The algorithm is based on analyzing the spectral curve in the "red-edge" band, which is sensitive to chlorophyll concentration and leaf cover density.

The index values were interpreted according to the chlorophyll activity scale: very low – < 1.8; low – 1.8–2.2; medium – 2.2–2.5; elevated – 2.5–3.0; high – 3.0–3.5; and very high – > 3.5.

Low OTCI values indicate suppressed vegetation, chlorophyll deficiency, or water/heat stress. Its elevated values indicate active photosynthesis and sufficient moisture and nutrient availability.

The OTCI was used in combination with the soil water index (SWI) to assess the interrelationship between soil water regimes and the photosynthetic productivity of agroecosystems.

Calculation of the Soil Water Index (SWI)

To assess moisture trends in the soil root zone, the SWI from the Copernicus Global Land Service, based on satellite data from the active microwave sensor ASCAT (MetOp, EUMETSAT), was used. The product's spatial resolution is 1 km, and the time step is 1 day (Copernicus Land Monitoring Service, 2024; González-Zamora *et al.,* 2016; Fathololoumi *et al.,* 2022).

The basic variable for calculating the SWI is Surface Soil Moisture (SSM), which characterizes moisture content in the topsoil (≈0–2 cm) and is determined based on the backward microwave scattering data. The SSM values are expressed in relative units (% saturation).

The SWI is obtained by applying the exponential filter to the SSM time series, which allows for simulating the inertia of moisture penetration into deeper soil horizons. It is calculated using the recursive formula (Copernicus Land Monitoring Service, 2024):

$$SWI_t = SWI_{t-1} + K_t(SSM_t - SWI_{t-1}) \quad (2)$$

where: SWI_t – soil water index at time *t*; SSM_t— soil surface moisture at time *t*; K_t – filtration coefficient; SWI_{t-1} – the index value on the previous day.

The filtration coefficient is determined as:

$$K_t = 1 - e^{-\frac{\Delta t}{T}} \quad (3)$$

where Δt – time interval (1 day); T – time inertia parameter (moisture penetration time).

The T parameter indicates the response rate of the index to changes in moisture and corresponds to a nominal depth of the soil layers:

SWI product	T (days)	Approximate depth
SWI002	2	0–5 cm
SWI010	10	10–20 cm
SWI020	20	20–40 cm
SWI040	40	>40 cm

The SWI002 product, which indicates the prompt response of surface soil and root zone to precipitation and evaporation, was used in the research. The choice of the SWI002 product was determined by its high sensitivity to short-term changes in the water regime of the soil root zone, which directly affect the early development of water stress in crops. It is this product that most promptly reflects the soil's response to precipitation deficits, intensive evaporation, and the cessation of irrigation, which are determining factors in the functioning of agroecosystems in the arid climate of Southern Ukraine.

The resulting values are standardized on a dimensionless scale of 0–100:

$$SWI = 100 \times \frac{SWI - SWI_{min}}{SWI_{max} - SWI_{min}} \quad (4)$$

The SWI is a relative indicator of water availability water in soil that accounts for regional soil and climatic conditions. The SWI values were unified to a range of 0–100 (0 → very dry, 100 → saturated with moisture) and classified according to water stress types (Tabl. 1). The lower the SWI, the less soil moisture is available to plants, and the more severe the water stress is, which manifests as stunted growth, a decline in photosynthetic activity, and a potential loss of yield. In contrast, high SWI values indicate good water supply and normal plant growth.

Table 1: Water stress types in plants and agronomic interpretation as indicated by the SWI.

SWI	Drought types	Water stress level in plants	Agronomic interpretation	Physiological and biochemical responses in plants	Potential effect on productivity
> 60	No drought (good conditions)	No water stress	Optimal water supply for crops	Active photosynthesis, maximum transpiration	No effect
50–60	Normal	Mild stress	Favorable conditions for plant growth and development	Partial regulation of stomata, adaptive reaction	Up to 5 %
40–50	The onset of drought (Watch)	Eearly stress	The onset of moisture deficit, stunted growth	Decline in photosynthetic activity	5–10 %
30–40	Agricultural drought (Warning)	Moderate stress	Inhibited plant growth	Closure of stomata, reduced biomass accumulation	10–25 %
20–30	Severe drought (Alert)	Severe stres	Stunted growth, leaf curl	A sharp decline in transpiration, activation of stress hormones	25–50 %
< 20	Extreme drought	Critical stress	Plant wilting and growth cessation	Destruction of photosynthetic apparatus	> 50 % or a loss of crops

The spatial characteristics of the OTCI and SWI were identified for agricultural lands in the Kherson region. For each research date, average index values were calculated using all valid pixels of agricultural land and the areas that belonged to the individual SWI and OTCI classes. The comparative analysis of spatio-temporal trends in the indices between 2021 and 2025 was conducted individually for the historical irrigated area, which had been in operation before the destruction of the Kakhovka HPP and the Reservoir's drainage, as this very area underwent the most significant transformations due to the cessation of irrigation water supply. This approach allowed for the accurate comparisons of changes resulting from the loss of irrigation within the unchanged spatial boundaries of the research.

To assess atmospheric drought, Selyaninov's hydro-thermal coefficient (HTC) was used (Polevoy *et al.,* 2024):

$$HTC = \frac{\sum P}{0.1 \sum T_{>10}} \quad (5)$$

where: $\sum P$— total precipitation for the period with an average daytime temperature of >10 °C; $\sum T_{>10}$— the sum of temperatures above 10 °C.

Moisture availability: 1.3 – excessive moisture; 1.0–1.3 – sufficient moisture; 0.7–1.0 – insufficient moisture; 0.5–0.7 – dry; <0.5 – very dry.

GIS technologies within the ArcGIS environment were used to model the studied processes spatially. The methodological framework was based on the comprehensive processing and integration of various types of spatial data, including satellite image interpretation, overlaying thematic layers, and subsequent thematic interpretation.

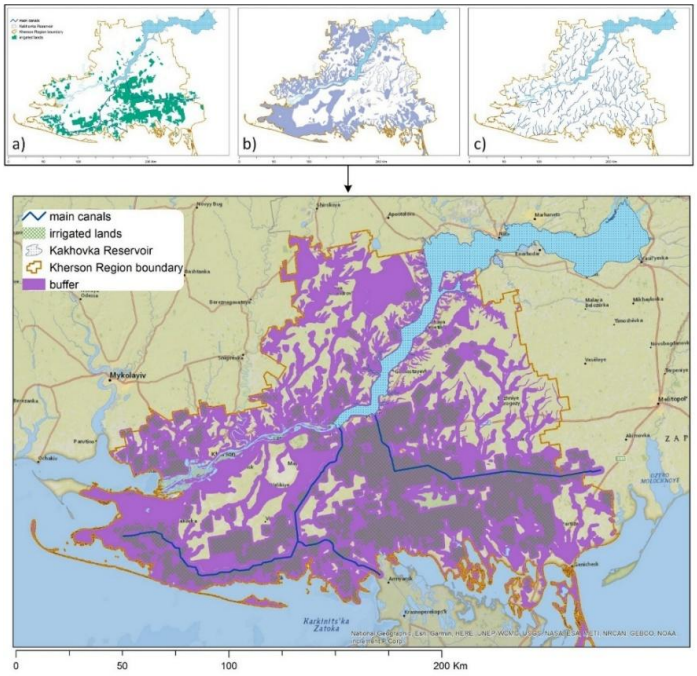
RESULTS

The pre-war functioning of irrigated agricultural landscapes

Until the beginning of a full-scale war, irrigated agriculture was a determining factor in the functioning of the Kherson region's agricultural sector and an important component of food security in Southern Ukraine. The Kakhovka Reservoir supplied irrigation water to about 77 % of the country's irrigated land (Pichura *et al.,* 2023). In the Kherson region, as of 2021, irrigation systems irrigated about 315 thousand hectares of agricultural land, which increased grain yields to 3.8–5.4 tons per hectare compared to 2.4 tons per hectare on non-irrigated land and created favorable microclimatic conditions in the irrigated area (Pichura *et al.,* 2023).

Sufficient soil moisture in the Kherson region was determined by the redistribution of precipitation along the thalwegs (natural water courses) and by the operation of the hydraulic network of irrigation systems. The horizontal redistribution of water flows occurred mainly from north to south across the region, maintaining water levels in water bodies and watercourses, a balanced water regime, and high biological activity in the soil cover. An important effect of this redistribution was additional replenishment of groundwater by fresh infiltration, which supplied drinking water and filled local residents' wells for domestic use.

Fig. 2: Hydraulic and hydrological distribution of moisture in the Kherson region: a – the location of irrigated lands and main canals; b – areas with a groundwater table depth of < 5 m; c – watercourses of the natural hydrological redistribution of moisture.



During its operation, the Kakhovka Reservoir served as a powerful hydrological barrier, contributing to increased groundwater levels in the right-bank part of the region. At the same time, the Reservoir was an important source of discharging water and maintaining optimal soil moisture content in the left-bank area. Freshwater ensured soil leaching and contributed to desalination, an increase in fresh groundwater reserves, and a decrease in mineralization. Fig. 2 shows the spatial features of the hydraulic and natural hydrological redistribution of moisture in the Kherson region; the integral map illustrates the areas of the combined effect of irrigation infrastructure (Fig. 2a), hydro-geological conditions (Fig. 2b), and a natural drainage network (Fig. 2c) on maintaining the regional water balance.

The quantitative parameters of water supply confirm the leading role of irrigation in replenishing the climate-related moisture deficit. Between 1966 and 2021, during the growing seasons characterized by moisture deficits (May–September), total precipitation (P) ranged from 155 to 330 mm from south to north. Irrigation (IN) additionally replenished natural moisture deficit by 80–200 mm and, in dry years, up to 300 mm. The total water supply (P + IN) in the irrigated areas was 345–410 mm (Fig. 3), which increased the bioclimatic potential of irrigated and adjacent agricultural landscapes by 1.2–3.0 times and raised crop yields by 2.5 times on average.

Fig. 3: Total natural and artificial (P + IN) water supply in the Kherson region in the growing seasons, 1966–2021: a – spatial distribution of moisture; b – dependence of irrigation volumes on precipitation.

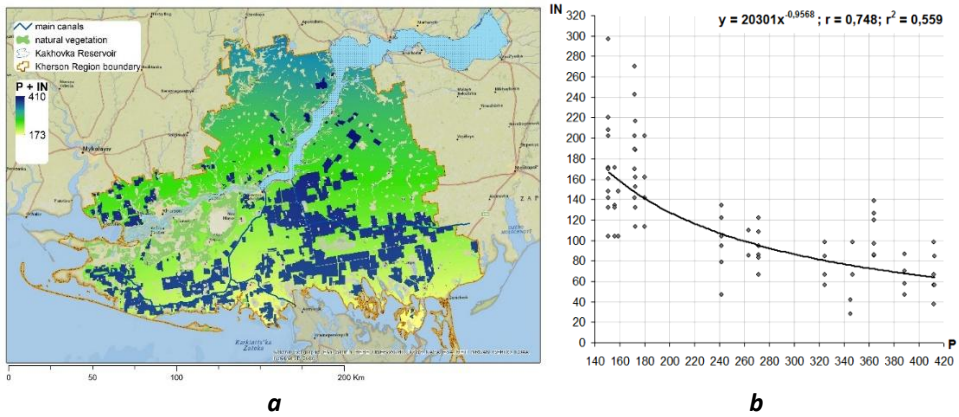


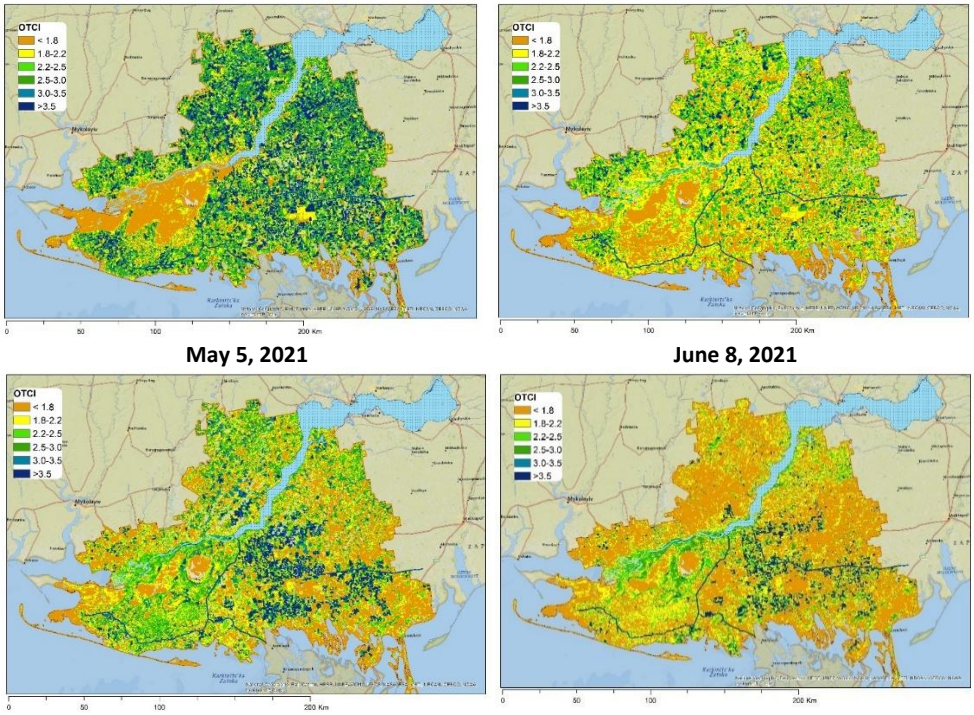
Fig. 3b shows a correlation between precipitation (P, mm) and irrigation volumes (IN, mm) during growing seasons characterized by moisture deficits. Based on data from long-term observations between 1966 and 2021, a power-law inverse non-linear relationship was established: as natural moisture content increases, the need for artificial water supply decreases. This confirms the compensatory role of irrigation in maintaining water balance in agricultural landscapes and stabilizing their productive potential. Accordingly, the total bioclimatic energy varied between 265 and 765 mJ/m² on non-irrigated lands during the growing season, and it ranged from 790 to 910 mJ/m² on irrigated lands (Pichura *et al.,* 2023). This ensured the agricultural sector's capacity for functional stability under conditions of significant moisture deficits and generated a complex of important ecosystem services of irrigated agricultural landscapes (productive, regulatory, climate-stabilizing, and social).

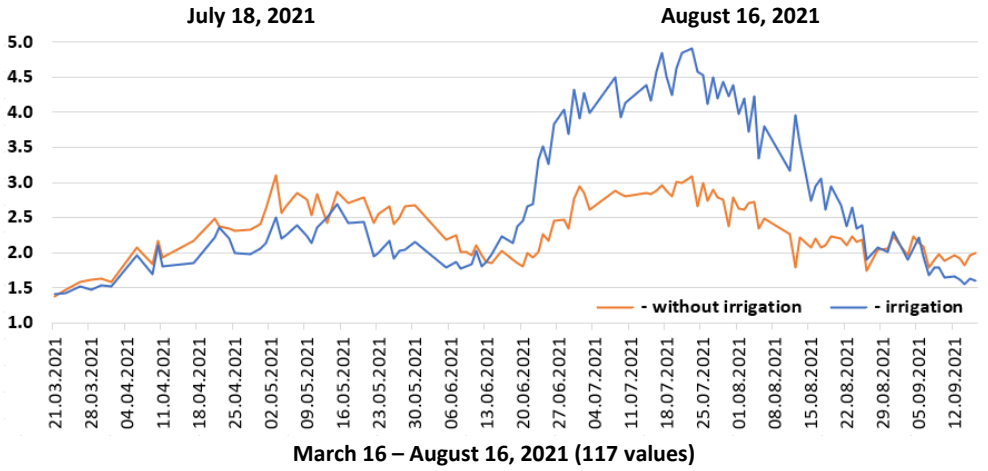
Satellite verification of bioproductivity and vegetation condition based on the OTCI (2021)

The identified water supply patterns are reflected in vegetation cover, its bio-productivity, and the intensity of photosynthetic processes. The spectral indices of chlorophyll content and plant density indicate the spatio-temporal response of agrocenoses to the combination of natural moisture and artificial water supply. To this end, analysis of the OTCI, an integral indicator of the health, moisture, and productive potential of vegetation cover, was conducted. Cartographic and graphic materials (Fig. 4) show the spatial differentiation of chlorophyll activity and seasonal trends in vegetation cover in the region's irrigated and non-irrigated areas during the 2021 growing season.

The cartographic analysis shows a distinct spatio-temporal differentiation of the OTCI values between May and August, 2021, and the evident dependence of vegetation condition on irrigation availability. In May, most of the area had elevated and high index values, corresponding to good natural moisture content and active photosynthesis in winter and early-spring crops. In June, high bioproductivity was observed mainly in irrigated areas, where late-spring crops were in the active initial phenological stage. In contrast, on non-irrigated lands, areas with medium and low index values were prevalent, which was determined by the end of the growing season for winter and early-spring crops and the slow development of late-spring crops due to an increase in moisture deficit. In July, the period of maximum heat loads, the contrast between non-irrigated and irrigated lands increased significantly: water stress was prevalent on non-irrigated lands, whereas elevated chlorophyll index values were observed on irrigated lands.

Fig. 4: Spatio-temporal trends in the OTCI and the role of irrigation in the formation of vegetation bioproductivity in the Kherson region (2021).





Note: According to the OTCI classification, below 1.8 – very low chlorophyll content; 1.8–2.2 – low chlorophyll content; 2.2–2.5 – medium chlorophyll content; 2.5–3.0 – elevated chlorophyll content; 3.0–3.5 – high chlorophyll content; above 3.5 – very high chlorophyll content. Values of <2.2 attest to significant water stress in plants; values of 2.2–2.5 – insufficient moisture content; values of 2.5–3.0 – satisfactory moisture content; values of >3.0 – good moisture content.

In August, an overall seasonal decline in the index values was observed. However, the phytosanitary condition of late-spring crops was better on irrigated lands. The timing OTCI diagram confirms the crucial role of irrigation: index values on irrigated lands consistently exceeded those on non-irrigated lands by 1.0–1.8 units. Overall, the results demonstrate that irrigation leads to higher bioproductive and chlorophyll potential in agricultural landscapes, mitigates the effects of water stress, and maintains the stability of vegetation cover in the region's dry climate.

Stages of examining the war-induced transformation of irrigated agricultural landscapes

The pre-war assessment of water supply and bioproductivity is fundamental to the interpretation of further changes during wartime. The full-scale military aggression, the occupation of a considerable portion of the region, and the destruction of the hydraulic infrastructure and the Kakhovka Reservoir have caused the cessation of irrigation system operations and triggered large-scale natural and anthropogenic transformations in the irrigated area.

To ensure the accuracy of the spatio-temporal comparison of agricultural landscape transformations, July was selected as the key period for analysis based on the results of long-term observations. It was characterized by the highest near-surface air temperatures and severe water stress. During this period, after harvesting winter and early-spring crops, critically important phenological stages (active growth, flowering, and biomass formation) of such late-spring crops as sunflower, corn, and soybean are observed on irrigated lands. This phenological specificity ensures the most striking difference in vegetation cover condition among irrigated, adjacent, and non-irrigated lands, creating optimal conditions for identifying the effects of the loss of irrigation.

The comparative analysis of satellite imagery enabled tracing the sequential degradation of the area during wartime. July 2021, which preceded the full-scale invasion, was characterized by active agricultural production, the operation of irrigation systems, and the

stable socioeconomic activity of territorial communities in the research area. In July 2022, against the backdrop of full-scale hostilities and the onset of occupation, there was a sharp decline in agricultural production, the depletion of most arable lands, the destruction of production infrastructure, and the aggravation of socioeconomic crisis. July 2023 marked a turning point in the region's natural resource transformation driven by the destruction of the Kakhovka HPP Dam and the Reservoir's drainage. The loss of the key water source caused the cessation of water supply to the main canals and their drainage, the acute exacerbation of water stress, the destruction of irrigated agriculture, and the deepening of the environmental and socioeconomic crisis, which, given its scale, was considered an ecocide. In July 2024–2025, under conditions of the prolonged occupation of the left-bank Kherson region, the further deepening of degradation processes, including a complete lack of irrigation, the destruction of crop production, a fivefold increase in the frequency of abnormally high temperatures, critical moisture deficits, and the emergence of semi-desert landscapes, was observed. The drainage of water bodies, the shallowing of watercourses, and large-scale fires in stubble fields and steppe biotopes were accompanied by a deepening socioeconomic crisis, impoverishment of the population, excess mortality, and degradation of the age structure in local communities.

Choosing July as a representative research period allowed for the most comprehensive reflection of the cascading dynamics of the war-induced degradation of agricultural landscapes – from high bioproductivity and optimal water supply to extreme water stress, thermal degradation, and the signs of desertification in the area. Further analysis of the spatio-temporal trends in the indices of vegetation, moisture, and thermal regime enabled a quantitative assessment of the extent of the war-induced transformation of irrigated ecosystems and clarified the key environmental effects of the loss of irrigation.

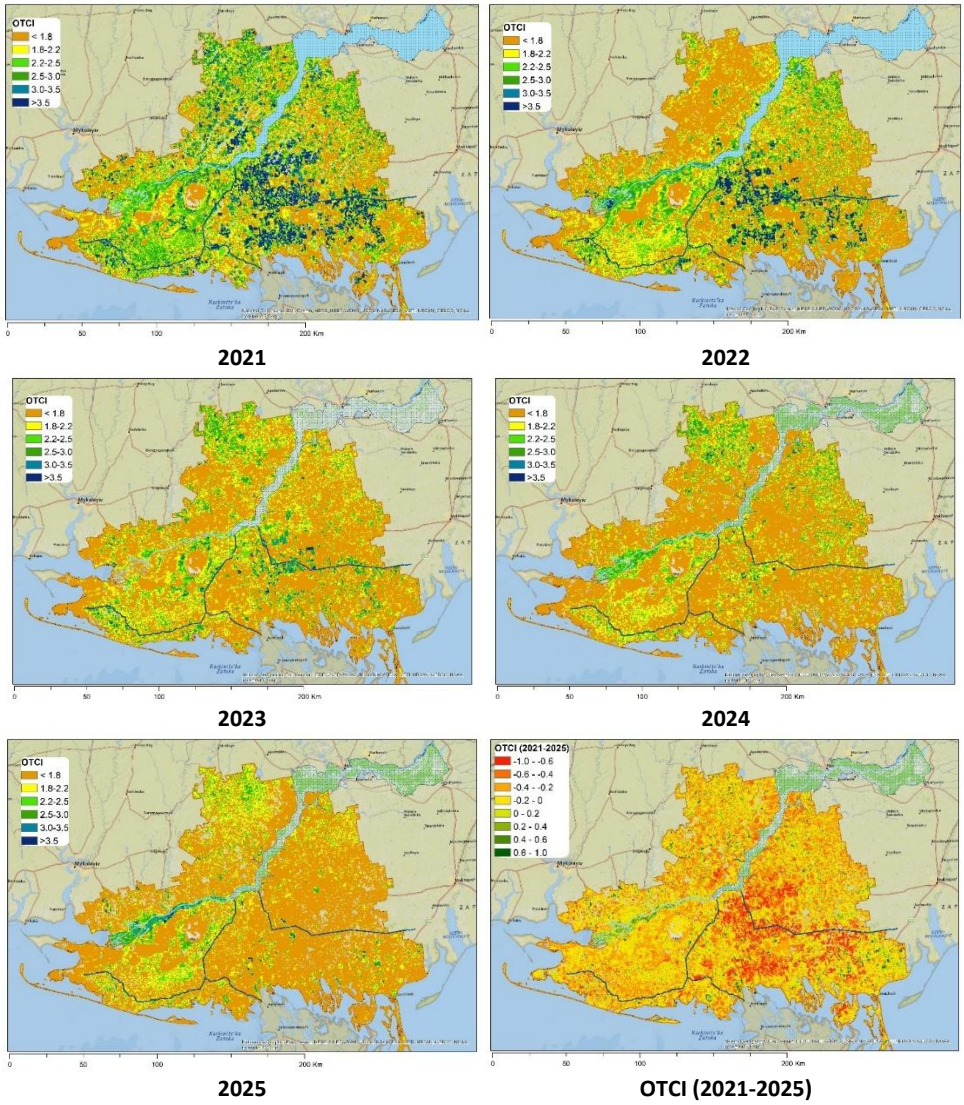
Spatio-temporal degradation of vegetation cover and bioproductivity as indicated by the OTCI (2021–2025)

The identified stages of the war-induced transformation are spatially reflected in the changes in chlorophyll activity and bioproductivity of vegetation cover. The war and the loss of artificial water supply have caused a sharp decline in bioproductive stability in the irrigated area and degradation of vegetation cover, as evidenced by satellite indices of bio-productivity and moisture. Fig. 5 shows the spatio-temporal transformation of vegetation cover in the Kherson region based on the OTCI between 2021 and 2025. Cartographic materials indicate a gradual decrease in plant bioproductivity and moisture content in the formerly irrigated area.

In July 2021, under active operation of the irrigation infrastructure, the area was characterized by elevated or high index values (>2.5–3.5 and >3.5), which corresponded to good water supply, dense vegetation cover, and intense growth of agrocenoses. In 2022, there was an increase in the area with medium and low OTCI values, attributed to a decline in agricultural production during wartime and a decrease in the area of cultivated lands by about 60 %. In 2023, after the destruction of the Kakhovka Reservoir, there was a sharp increase in the area with low index values (<2.2), which attests to critical water stress, vegetation cover degradation, and the destruction of agricultural production in the occupied areas; the area under crops decreased by 80 % compared to the pre-war period. In 2024–2025, degradation processes deepened, resulting in extensive areas with low chlorophyll activity and the expansion of bare soil and degraded lands. In the left-bank occupied area, about 7 % of agricultural land was used for production, whereas most areas were characterized by bare

soil, dead wood, or degraded steppe plants; the percentage of the area with developed vegetation cover did not exceed 20 %.

Fig. 5: Spatio-temporal trends in the OTCI and vegetation cover degradation in the Kherson region's irrigated ecosystems in 2021–2025.

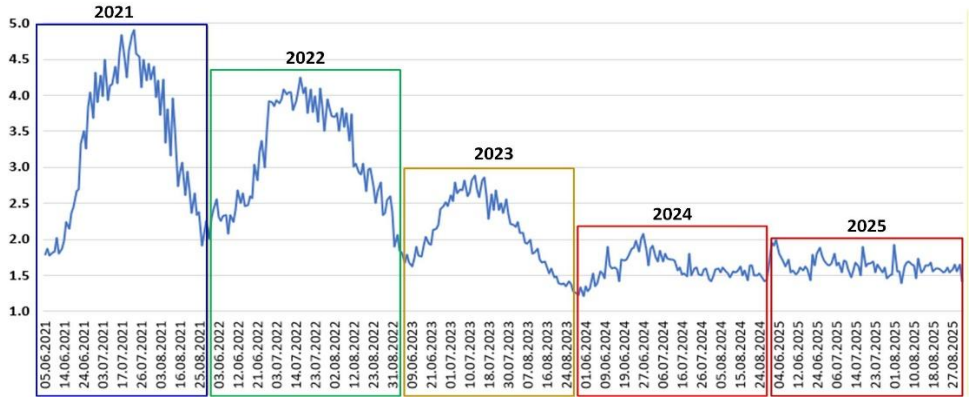


In 2024, due to groundwater discharge, a deterioration in natural moisture supply, and the onset of soil drought, about 40 % of areas under crops were lost in the right-bank Kherson region. In the 20-kilometer frontline area along the Dnipro River, Russian troops intentionally destroyed crops using drone attacks. In 2025, the situation significantly deteriorated due to a combination of spring frosts, spring-summer droughts, and intentional crop burning, which caused the loss of up to 80 % of the area, while the remaining 20 % experienced critically low crop yields. The integral map of the OTCI changes (2021–2025)

shows the patches with the sharpest decline in bioproductivity, which spatially correspond to the areas without irrigation water supply and the drainage of irrigated systems, confirming the crucial role of irrigation in maintaining the bioproductive potential and ecological stability of the region's agricultural landscapes.

Further quantitative verification of the identified spatial patterns is shown in Fig. 6, which shows the OTCI trends (381 values) on irrigated lands.

Fig. 6: Long-term trends in the OTCI in the Kherson region's irrigated areas in 2021–2025 (June–August).



In 2021, under irrigation, the OTCI reached 4.5–4.8 at peak plant growth stages, corresponding to very high chlorophyll content, good moisture content, and intensive photosynthesis in plants. In 2022, the first significant decrease in the index was observed: maximum OTCI values did not exceed 3.8–4.0, and the duration of high-productivity period was shorter, indicating the partial disruption of irrigation and agricultural production. In 2023, after the destruction of the Kakhovka HPP Dam and the cessation of water supply, there was a sharp decrease in index values: peak OTCI values fell to 2.5–2.8, indicating insufficient moisture and attesting to the systemic degradation of vegetation cover in the formerly irrigated areas.

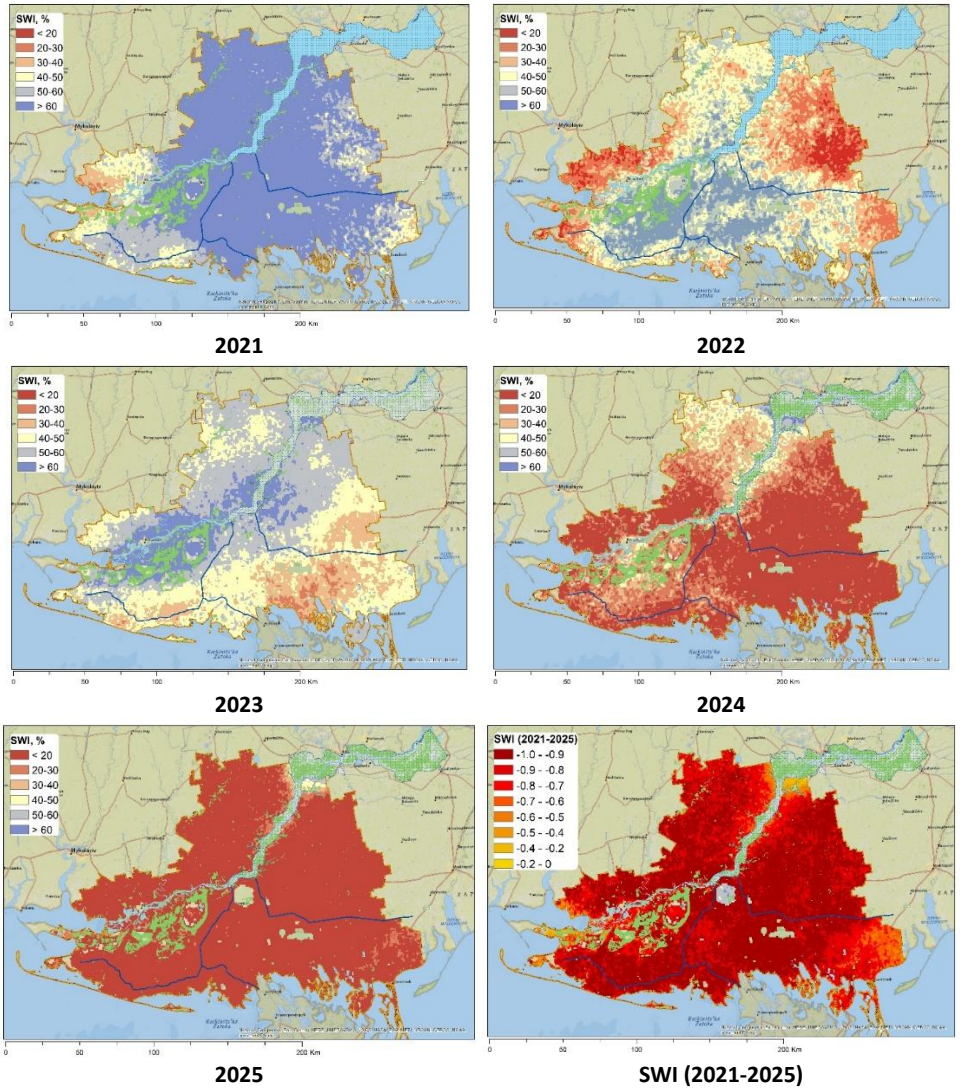
In 2024, the downward trend was more pronounced: the OTCI values ranged from 1.4 to 2.0, corresponding to low chlorophyll content and significant water stress in plants; growth peaks were almost smoothed out, indicating a loss of agrocenosis production stability and a decline in crop production in the occupied left-bank area. In 2025, persistent degradation of vegetation cover is observed: the OTCI values fluctuate within a narrow range of 1.5–1.8, without apparent seasonal peaks, which attests to the manifestations of water bankruptcy, the development of soil drought, agricultural landscape degradation, and the signs of aridified and semi-desert ecosystems.

Spatio-temporal trends in soil moisture and water stress in plants as indicated by the SWI (2021–2025)

Since degradation as indicated by the OTCI reflects the response of plants to moisture deficit, the next step was to assess the primary component, soil moisture, using the SWI. The cartographic analysis of the spatio-temporal trends in the SWI attest to the profound transformation of water regime and a sharp increase in water stress in the Kherson region's

vegetation cover between 2021 and 2025 (Fig. 7). The results correspond to the loss of irrigation water supply, the destruction of the hydraulic infrastructure, and the drainage of the Kakhovka Reservoir, which performed the key water-regulating function in the region.

Fig. 7: Spatio-temporal trends in the SWI in the Kherson region in 2021–2025.



In the pre-war period (2021), most of the region's area was characterized by high SWI values (>50–60 and >60), indicating no or low water stress in plants. The maximum soil moisture values were observed in irrigated areas and adjacent agricultural landscapes, where the operation of main canals and intra-farm irrigation networks ensured a stable water supply, optimal growing conditions, and the active accumulation of crop biomass. In 2022, against the backdrop of the full-scale war and the partial disruption of irrigation regimes, areas with SWI values of 30–50 expanded, corresponding to initial and moderate water stress. These

changes were mainly manifested spatially in southern and western regions, where irrigated area and water supply volumes decreased. However, in some irrigated areas, relatively favorable conditions could still be found, indicating certain inertia in the operation of irrigation systems at the beginning of the war.

The year 2023 marked a turning point in the water regime transformation: after the destruction of the Kakhovka HPP Dam and the cessation of water supply to main canals, a sharp decline in the SWI values was observed. There were more areas with SWI values of 20–40, which corresponded to agricultural and severe droughts. The drainage of canals, the loss of infiltration feeding, and the cessation of artificial irrigation caused systemic soil moisture deficit, suppressed vegetation, and a sharp decline in agrocenosis bioproductivity. In 2024, large-scale water regime degradation was observed: the greater part of the area was characterized by critically low SWI values (<20–30), corresponding to severe and critical water stress in plants; extensive drainage of arable soil layers and drought were observed. The patches of relatively higher moisture content were found only locally – in the Dnipro floodplain, in low-lying areas, and in areas with natural hydrological moisture redistribution. In 2025, a steady phase of hydrological degradation was observed: almost the entire area was in an extreme drought zone (SWI <20), which attests to persistent soil moisture deficit, the loss of the irrigation network's water-regulating function, and the preconditions for landscape aridification.

The integral map of SWI trends for 2021–2025 shows patches with the sharpest declines in soil moisture that spatially correspond to areas without irrigation water supply, areas with drained irrigation canals, and areas formerly dependent on the Kakhovka Reservoir. This confirms the crucial role of the hydraulic infrastructure in maintaining the water balance, bio-productivity, and ecological stability of agricultural landscapes in Southern Ukraine.

The long-term seasonal diagrams (Fig. 8) of SWI trends quantitatively complement the cartographic analysis and reflect the depth of water-regime transformations on irrigated lands.

In 2021, SWI values consistently remained within a range of 50–80, corresponding to optimal and good moisture and no water stress. Since 2022, there has been a decrease in the amplitude of seasonal fluctuations and in the maximum SWI values, which attests to the disruption of water supply and a reduction in irrigated areas. A critical decrease in SWI values was observed in 2023 after the loss of water supply; its summer values fell to 20–30, corresponding to severe water stress.

In 2024, the SWI values consistently remained at 10–25, leading to persistent moisture deficit. In 2025, fluctuations occurred within a narrow range (SWI <20) without seasonal peaks, indicating prolonged soil drought and a loss of agricultural landscapes' ability to accumulate moisture. The seasonal analysis shows that the most intensive degradation was observed in summer, during the phase of crops' maximum water use, when irrigation replenished the climate-related moisture deficit under normal conditions. After the loss of water supply, summer was a critical period of soil drought and a sharp decline in bioproductivity.

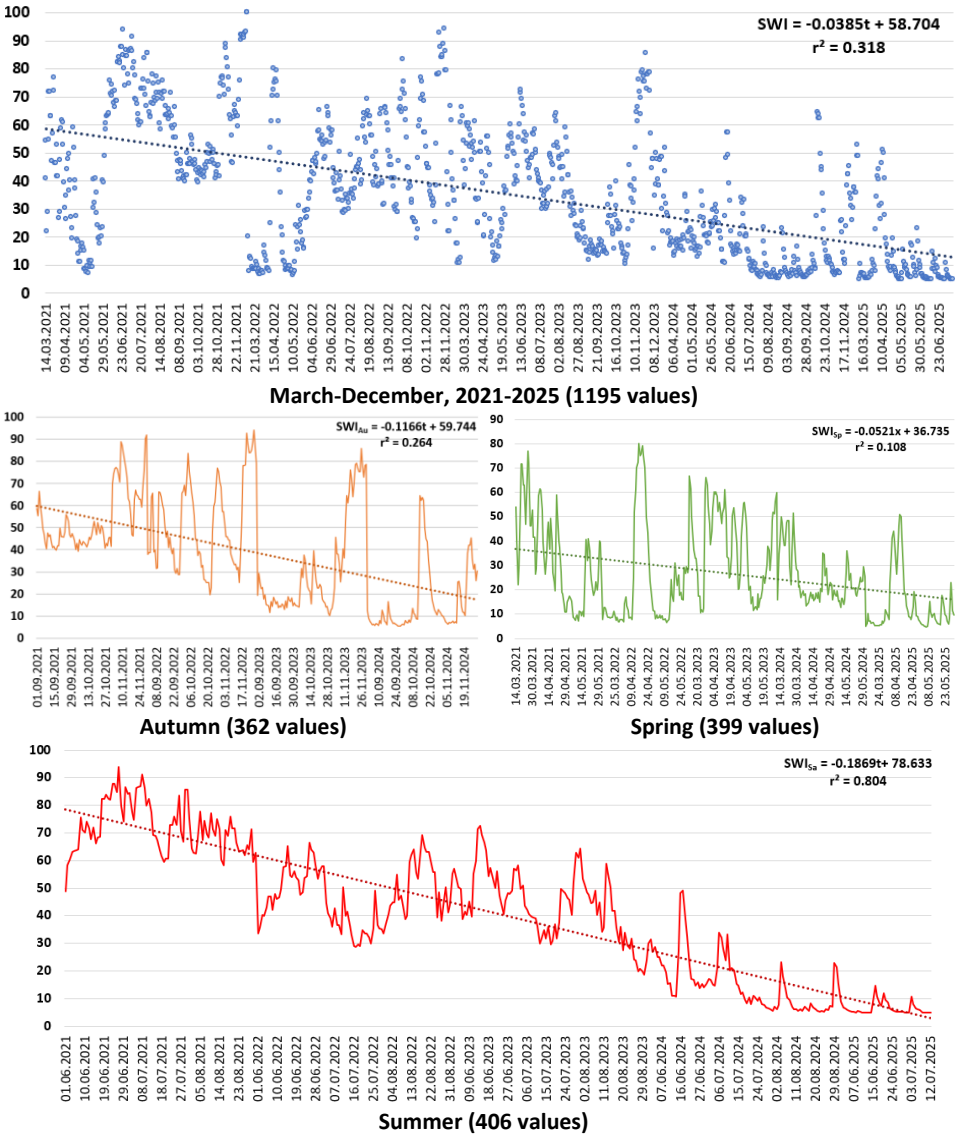
Transformation of thermal and hydrothermal conditions in the growing season and their effects on the productivity of agroecosystems.

In addition to the disrupted water regime, the causal analysis of the degradation of irrigated agricultural landscapes considered the transformation of thermal and hydrothermal conditions in the growing season, which results in integrated heat and drought stress and affects the intensity of aridification processes. To this end, a set of thermal and hydrothermal

indicators was analyzed for July 2021–2025, in Kherson, the representative meteorological center of the irrigated area in Southern Ukraine.

The subset of thermal indicators included the average monthly air temperature, its deviation from the 1991–2020 climatological normal, the sum of positive temperatures (ΣT>10 °C), the number of days with a maximum temperature exceeding +35 °C, and maximum daytime and average nighttime temperatures. This subset of indicators enables a comprehensive assessment of the intensity of thermal fluctuations, the exposure of vegetation cover to heat loads, and the potential manifestations of heat and drought stress under conditions of disrupted or absent irrigation.

Fig. 8: Long-term and seasonal trends in the SWI on irrigated lands in the Kherson region in 2021–2025.



July is a critical phenological phase for late-spring crops, including flowering, pollination, and the initial formation of generative organs in corn, sunflower, soybean, and vegetable crops. At this time, crops achieve their maximum yield potential, and the water regime becomes extremely sensitive to temperature extremes. Under irrigated conditions, artificial water supply replenished atmospheric moisture deficits, maintained optimal soil moisture, ensured the transpiration cooling of the leaf area, and partially mitigated the negative effects of thermal fluctuations. Therefore, during hot days in irrigation periods, the thermal load was not converted into critical moisture deficit, and the productivity of agrocenoses remained relatively stable.

In 2021–2022, July temperature were characterized by values approaching the climatological normal (Table 2). The average monthly temperatures were 24–26 °C, and deviations from the normal were within a range of 0…+2 °C. Under these conditions, the sum of positive temperatures ensured a sufficient heat supply for agrocenoses (744–806 °C), days with T_{max} >35 °C were infrequent (0–3 days), and nighttime temperatures were largely below +20 °C (16–19 °C). Under irrigated conditions, heat stress was low to low-moderate and did significantly reduce climate-driven productivity.

Table 2: Climate indices and indicators of heat stress in the Kherson region's agroecosystems in July, 2021–2025 (Meteostat, NOAA GSOD, ERA5-Land).

Year	Average t°, °C	Deviation from the normal, °C	Year's characteristics	ΣT>10 °C	Days >35 °C	Tmax, °C	Nighttime t°, °C	Assessment of heat stress
2021	24–25	+0…+1	Normal	744–775	0–2	31–33	16–18	Low
2022	25–26	+1…+2	Warm	775–806	1–3	32–35	17–19	Low–moderate
2023	25–26	+1…+2	Warm	775–806	3–5	34–36	18–21	Moderate
2024	27–28	+3…+4	Very hot / extreme	837–868	8–12	39–42	21–24	Extreme
2025	26–27	+2…+3	Very hot	806–837	5–8	37–39	20–22	High

Note: the climatological normal in July ≈ +24,0 °C

In 2023, there was a transition to a consistently warmer regime: the average temperature in July was 25–26 °C (a deviation of +1…+2 °C), the sum of positive temperatures rose to 775–806 °C, and the number of extremely hot days (T_{max} >35 °C) increased to 3–5. The nighttime temperatures approached the threshold for "warm nights" (18–21 °C), indicating the onset of moderate heat stress, increased respiratory losses, and a gradual rise in evaporative demand. At the same time, despite higher temperatures, precipitation was 40–50 mm (Table 3), which corresponded to or slightly exceeded the climatological normal and temporarily mitigated atmospheric moisture deficits. However, this increase in atmospheric moisture did not replenish high evaporation volumes and failed to prevent the loss of productive soil moisture. The situation became more complicated due to the Kakhovka Reservoir's drainage, which led to a reduction in groundwater levels, disruption of capillary water supply to the arable layer, and increased aridity in agricultural landscapes.

Since 2024, a radical transformation of the thermal regime has been observed. The average temperature in July rose to 27–28 °C (+3…+4 °C compared to the normal), and the sum of positive temperatures increased to 837–868 °C, exceeding this parameter's value in 2021 by 80–110 °C. The number of days with T_{max} >35 °C increased to 8–12, and the maximum daytime temperatures reached 39–42 °C. In addition, the effect of "warm nights" was clearly noticeable: the average nighttime temperatures rose to 21–24 °C. The combination of these factors accelerated the phenological phases in plants, shortened the grain-filling phase,

increased potential evaporation, and decreased the efficiency of photosynthetic processes, indicating extreme heat stress.

Table 3: Hydrothermal conditions and indicators of atmospheric drought in the Kherson region in July, 2021–2025 (according to data from Meteostat, NOAA GSOD, ERA5-Land).

Year	Precipitation, mm	Deviation from the normal, mm	HTC	Moisture availability	ET_0, mm
2021	30–35	−5…−10	0,46–0,53	Dry	160–170
2022	15–25	−15…−25	0,27–0,45	Very dry	170–180
2023	40–50	0…+10	0,50–0,62	Close to normal	155–165
2024	10–15	−25…−30	0,12–0,18	Extremely dry	210–230
2025	14–15	−25…−26	0,17–0,19	Extremely dry	195–210

Note: the climatological normal in July ≈ 40 мм

Increased heat loads were accompanied by the synchronous deepening of atmospheric drought. In 2021, precipitation deficit was relatively moderate (30–35 mm; −5…−10 mm compared to the normal). However, in 2022, it increased significantly: precipitation fell to 15–25 mm, and the hydrothermal coefficient decreased to a value characteristic of very dry conditions. A critical hydro-climatic transformation occurred in 2024, when precipitation fell to 10–15 mm, the hydro-thermal coefficient fell to 0.12–0.18, and potential evaporation exceeded 210 mm, resulting in severe water imbalance in the middle of the growing season. The combination of extreme heat and atmospheric moisture deficit caused a sharp increase in evaporation and productive soil moisture deficit.

In 2025, despite a slight decrease in temperature compared to the extreme year of 2024, the weather remained very hot. The average temperature in July was 26–27 °C (+2…+3 °C compared to the normal), and the number of days with Tmax >35 °C reached 5–8, maintaining high heat loads. At the same time, the aridification of climatic conditions remained at an extremely high level: precipitation was only 14–15 mm (≈35–40 % of the normal), the hydrothermal coefficient was 0.17–0.19, while potential evaporation remained high (195–210 mm). Such a disparity between atmospheric moisture and evaporation indicates the incapacity of precipitation to replenish lost moisture, which led to the onset of persistent atmospheric and soil droughts during critical phases of crop growth.

The climate-driven aridification directly affected the productivity of agricultural landscapes. Yield trends in 2021–2025 indicate a gradual transition from highly productive irrigated agriculture to extreme rainfed agriculture (Table 4).

In 2021, under irrigated conditions, grain yields amounted to 4.5–5.0 tons per hectare, and sunflower yields were 2.2–2.6 tons per hectare. In 2022, due to the effects of war and partial disruption of water supply, yields fell to 3.0–3.5 and 1.5–1.8 tons per hectare, respectively.

After the destruction of the Kakhovka HPP in 2023, agricultural landscapes lost their main source of irrigation water, leading to a decrease in grain yields to 2.0–2.5 tons per hectare. In 2024, during the first full season without irrigation, crop productivity was determined solely by natural moisture against the backdrop of extreme heat and precipitation deficit (10–15 mm), which limited grain crop yields to 2.4–2.6 tons per hectare and sunflower yields – to 0.8–1.0 tons per hectare.

The most critical situation was observed 2025, when the combination of extreme atmospheric and soil droughts, high temperatures, precipitation deficit, spring frosts, and a complete lack of irrigation water caused a sharp decline in crop yields: grain crop yields – to 1.2–1.4 tons per hectare and sunflower yields – to 0.2–0.7 tons per hectare, which was by

70–90 % below the pre-war level. Significant crop losses were observed in an area of about 60 thousand hectares.

Table 4: Trends in the average yields of main crops in the research area (the Kherson region).

Year	Crop yields, tons per hectare (Mean ± range)		Decline in crop yields, % until 2021		Main factors
	Grain crops	Sunflower	Grain crops	Sunflower	
2021	4.75 (4.5–5.0)	2.40 (2.2–2.6)	–	–	Full operation of irrigation systems
2022	3.25 (3.0–3.5)	1.65 (1.5–1.8)	−31.6	−31.3	Military operations, the partial disruption of water supply
2023	2.25 (2.0–2.5)	1.20 (1.0–1.4)	−52.6	−50.0	The Kakhovka Dam's destruction and the Reservoir's drainage, the cessation of irrigation water supply
2024	2.50 (2.4–2.6)	0.90 (0.8–1.0)	−47.4	−62.5	The first full season without irrigation; extreme heat and precipitation deficit
2025	1.30 (1.2–1.4)	0.45 (0.2–0.7)	−72.6	−81.3	Atmospheric and soil droughts, spring frosts, no irrigation

The combination of thermal, hydrothermal, and production indicators attests to the progressive degradation of agricultural landscapes. The loss of irrigation, combined with intensified temperature fluctuations and precipitation deficits resulted in a synergistic effect of aridification, which manifests as increased evaporative losses, a pronounced productive soil moisture deficit during the critical phases of organogenesis, and a sharp decline in agricultural crop yields in Southern Ukraine.

DISCUSSION

The results confirm that the war-induced destruction of the Kakhovka Reservoir's water management complex and the resulting cessation of water supply to main canals have triggered the degradation of irrigated agricultural landscapes in the Kherson region. The identified trajectory of changes follows a clear cascade logic: the initial hydrological loss of the water-regulating function → fast depletion of soil moisture reserves (SWI) → a decline in chlorophyll activity and plant bioproductivity (OTCI) → an increase in thermal and hydrothermal stress during the critical phenological phases → a sharp decrease in crop yields and the manifestations of aridification.

Using the SWI and the OTCI enabled a comprehensive assessment of the effects of the transformation of agroecosystems, from regulated water balance with high production stability in 2021 to persistent moisture deficit and plant degradation in 2024–2025. The consistency of the index trends is fundamentally important: the SWI indicates the state of the initial resource, productive soil moisture, whereas the OTCI reflects the biological response of vegetation cover manifested as a change in chlorophyll content and photosynthetic intensity. Their simultaneous decline testifies to degradation caused by moisture deficit, which is further amplified by climate extremes.

The spatial analysis showed a clear overlap of the degraded patches on the boundaries of formerly irrigated areas and the areas directly dependent on the Kakhovka Reservoir. This confirms the crucial role of irrigation as an agro-technological factor and the indispensable

component of the regional water-regulating system, which ensured infiltration feeding, the stability of groundwater levels, and the maintenance of productive water balance (Pichura *et al.,* 2023; Pichura *et al.,* 2025a; Romashchenko *et al.,* 2025). The loss of this function led to extensive areas being classified as patches under severe and critical water stress, resulting in subsequent bioproductive degradation (Pichura & Potravka, 2025; Vyshnevskyi & Shevchuk, 2024; Snizhko *et al.,* 2024).

At the same time, the results show the inertia in the operation of irrigation systems at the beginning of the war. In 2022, despite water supply disruptions, the SWI and OTCI values remained relatively high in some areas. This can be attributed to the residual effect of water regulators and the accumulated reserves of productive moisture, which ensured the buffering capacity of agricultural ecosystems (Pichura *et al.,* 2023). The year 2023, after the destruction of the Kakhovka HPP Dam and the Reservoir's drainage, marked a turning point that led to the loss of hydrological balance and the transition to climate-driven drought in agricultural landscapes (Vyshnevskyi *et al.,* 2023; Pichura *et al.,* 2025a).

The synergistic interaction between hydrological degradation and temperature extremes is of particular importance. The increase in surface temperature and the intensification of evaporation processes observed after the loss of irrigation are consistent with remote sensing data, which indicate a substantial increase in heat loads and accelerated soil moisture losses (Snizhko *et al.,* 2024; Pichura & Potravka, 2025). Between 2024 and 2025, a sharp rise in the number of days with T_{max} >35°C and the effect of "warm nights" transformed heat stress into a combined heat and drought stress, which is particularly harmful at the phases of blooming and fruit development. During this period, no seasonal SWI and OTCI peaks were observed, as the system entered a state of persistent dehydration with no possibility of seasonal recovery.

From the perspective of landscape ecology, these processes can be viewed as the formation of an alternative stable state in the formerly irrigated area – the transition from highly productive agroecosystems to aridified areas with degraded vegetation cover (Lisetskii & Pichura, 2016; Pichura & Potravka, 2025). Remote sensing data also indicate bare soils, an increase in the area without vegetation, degradation of steppe biotope, and intensified desertification processes (Pichura *et al.,* 2025a).

This transformation is self-reinforcing: the reduction of vegetation cover diminishes shaded areas, decreases moisture accumulation, impairs soil structure, and increases soil surface temperature. This triggers deflationary processes. In particular, in September 2024, large-scale manifestations of wind erosion were observed, with some patches ranging from 100 to 3000 hectares (Pichura & Potravka, 2025). The analysis of a satellite image from Sentinel-2, as of September 15, 2024 (https://browser.dataspace.copernicus.eu/), attests to intense erosion, the transport and accumulation of topsoil, the formation of thick dust plumes, and spatially distributed patches of deflation in the Kherson region. At the time of image capture, there was virtually no vegetation cover, and the soil surface remained bare, creating conditions for catastrophic wind erosion. According to the results of the preliminary modeling of potential soil losses under conditions of extreme dust storms in the steppe zone of Southern Ukraine (Dudiak *et al.,* 2021), estimated soil losses could amount to 150–300 tons per hectare, and, in the local centers of deflation, they could reach 600 tons per hectare. These estimations align with the satellite observations of the dust storm on September 15, 2024. However, the above values should be treated as potential losses rather than as the results of actual field measurements. For the largest patch, with an area of about 3.0 thousand hectares, the total volume of potentially transported soil could be 0.9–1.8 million tons. This confirms that degradation as indicated by the SWI and the OTCI is a long-term and systemic rather than temporary phenomenon.

Hydrological transformation additionally manifests as the drainage of water bodies, a decrease in groundwater levels, secondary soil salinization, and the degradation of river and wetland ecosystems, which further limit natural mechanisms for soil moisture replenishment (Snizhko *et al.,* 2024; Pichura *et al.,* 2025a). Taken as a whole, these create a complex chain of degradation changes, ranging from moisture deficits to soil-landscape and bioproductive transformations.

Thus, the loss of irrigation has become a basic driver of negative transformations, amplified by war-induced and climate-related factors. The destruction of water-regulating systems has led to the simultaneous hydrological, bioproductive, and hydrothermal degradation of agricultural landscapes, whose consequences extend beyond short-term yield losses and create preconditions for long-term aridification and a decrease in bioclimatic stability in Southern Ukraine.

CONCLUSIONS

The research findings confirm a systemic transition from irrigation stability to aridification in Southern Ukraine, caused by the war-induced destruction of the Kakhovka Reservoir and irrigation infrastructure. Using agricultural landscapes in the Kherson region as an example, it was found that until 2021, irrigation maintained water balance and supported high production and ecological stability across about 315 thousand hectares. Irrigation water played a key role in infiltration feeding and natural hydrological moisture redistribution beyond irrigated areas, maintaining groundwater levels and soil moisture content, ensuring soil leaching, and mitigating the risk of secondary salinization. Taken as a whole, these performed environmental functions and delivered bioclimatic and ecosystem services on irrigated landscapes.

The remote monitoring of pre-war conditions highlighted the crucial role of irrigation in maintaining bioproductivity: in 2021, OTCI values on irrigated lands consistently exceeded those on non-irrigated lands by 1.0–1.8 units, indicating higher chlorophyll activity and photosynthetic intensity in plants.

The year 2023 marked a turning point in regional hydrological destruction: after the Dam's collapse, water supplies were cut off, and agroecosystems transitioned from a regulated irrigation regime to climate-driven drought. The SWI fell from optimal values in 2021 to critical values (below 20) in 2024–2025, indicating the onset of persistent dehydration and the loss of seasonal soil moisture replenishment.

The simultaneous decrease in the SWI and the OTCI confirms the moisture-related nature of degradation. The peak OTCI values fell from 4.5–4.8 in 2021 to 1.4–2.0 in 2024–2025, indicating the transformation of highly productive irrigated systems into degraded lands with moisture deficits. The patches of extreme adverse changes spatially correspond to the formally irrigated areas.

The loss of irrigation coincided with the intensification of thermal and hydrothermal extremes in 2024–2025, resulting in a synergistic effect of aridification and a 70–90 % reduction in crop yields compared to pre-war yields. The identified trends attest to the new, low-productive, and unstable state of agricultural landscapes and necessitate the creation of scenarios for the post-war reconstruction of irrigation systems.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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