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The Future of Irrigation in Ukraine

Ranu Sinha, Poolad Karimi, Lorenzo Rosa, and Silvan Ragettli

EXECUTIVE SUMMARY

Prior to Russia’s invasion in early 2022, Ukraine was a prominent global producer and exporter of agricultural commodities, particularly grains. However, the invasion severely disrupted agricultural activities, causing decreased productivity and significant harm to irrigation infrastructure, estimated at roughly US$190 million. This disruption resulted in noticeable food shortages on a global scale. Adding to these challenges is the looming threat of climate change, which poses a gradual yet significant risk to Ukraine's agriculture sector. To effectively plan for post-invasion recovery and rebuilding, it is crucial to conduct a comprehensive analysis of the combined impacts of the invasion and global warming on the irrigation sector.

This analytical report examines the impact of climate change and Russia’s invasion of Ukraine on country’s irrigated agriculture. It aims to inform national water resources management policies and guide infrastructure investments in water storage and irrigation systems for post-invasion reconstruction and recovery planning. The assessment covers the period 2017 - 2022 and includes an analysis of the extent, performance, productivity, and water consumption in irrigated agriculture before the invasion. The effects of the invasion on irrigation productivity and coverage were also quantified, while also assessing the impact of climate change on agricultural production and exploring the potential of expanding irrigation to address future water scarcity. This analysis focus on four dominant crop types, namely maize, soybean, sunflower, and wheat & barley. We made use of the remote sensing-based water accounting tools to calculate key statistics on the total cropped area and on the crop-specific water balance under current and future water availability conditions at different administrative levels. The baseline data sources used include remote sensing technologies and agricultural statistics from Ukraine's census.

The analysis reveals that, prior to Russia’s invasion, only 1.6% of Ukraine's cropland was under irrigation and were primarily located in the southern oblasts. Soybeans and maize are among water-intensive crops and highly dependent on irrigation, accounting for 56% of total irrigation water consumption and occupying 32% and 16% of the nation's irrigated lands, respectively. This highlights the significant reliance of Ukraine's crucial crops on irrigation. Notable regional disparities and year-to-year fluctuations in irrigation water requirements were identified, with water consumption for irrigation increasing by up to 50% during drought years. Prior to the invasion, results show that irrigated crops consistently outperformed rainfed crops, with yields of irrigated crops ranging from 5% to a remarkable 80% higher productivity compared to similar crops grown under rainfed conditions.

The impact of the invasion on agricultural production is substantial. In 2022, Ukraine experienced a 13% reduction in its total irrigated areas compared to pre-invasion conditions, mainly due to irrigation systems located in regions not under government control or affected by ongoing hostilities, resulting in significant declines of up to 58% in irrigated areas in these regions. These effects are evident in overall agricultural productivity, with quantified losses of 14% in maize production, 30% in wheat & barley, 17% in soybean, and 21% in sunflower. The destruction of the Kakhovka reservoir has exacerbated the agricultural issues in Ukraine. This reservoir was a primary water source for major irrigation systems in the southern region, making its absence severely detrimental to irrigated agriculture. We estimate that 67% of Ukraine's pre-invasion

irrigated areas will be adversely affected due to the lack of water supply resulting from this event. This is expected to result in production losses of around 30% for 2023, and a projected increase of 36% in subsequent years. An additional concern in the ongoing invasion is the deteriorating water quality, which poses a potential threat to Ukraine's agricultural sector, as evidenced by water pollution in irrigation reservoirs.

For evaluating the potential effects of climate change on irrigated agricultural systems in Ukraine, this study performed an estimation of the agricultural areas susceptible to green water scarcity (GWS) under different global warming scenarios, specifically, 1.5°C and 3°C. GWS refers to conditions where there is insufficient rainfall for optimal crop growth, necessitating irrigation for increased yields. Results show that under current baseline climatic conditions, approximately 10% (3.1 million hectares, Mha) of Ukraine's rainfed croplands are vulnerable to GWS. However, with a 1.5°C and 3°C global temperature increase, the extent of cropland affected by GWS is projected to rise significantly, encompassing 41% (13.5 Mha) and 77% (25.5 Mha) of Ukraine's total cropland area, respectively.

Our analysis identified croplands where irrigation can effectively address the issue, making use of available renewable water resources (surface and groundwater) while ensuring responsible water consumption that does not harm environmental flows or deplete freshwater stocks. Under baseline climate conditions, roughly 60% (1.8 Mha) of cropland affected by GWS in Ukraine is suitable for sustainable irrigation expansion. As temperatures rise, the portion of GWS-affected cropland suitable for such expansion is projected to increase. In a 1.5°C and 3°C warmer climate, this figure reaches 69% (9.3 Mha) and 70% (17.8 Mha) respectively. Conversely, croplands facing GWS where water will not be locally available for irrigation expansion will increase from 1.3 Mha under baseline climate to 4.1 Mha and 7.7 Mha in a 1.5°C and 3°C warmer climate, respectively. In the analysis, along with southern region, the east-central regions of Ukraine emerge as hot spots for water scarcity due to climate change, making them unsuitable areas for irrigation expansion.

A sustainable reconstruction plan of Ukraine's irrigation sector post-invasion necessitates effective and collaborative planning. This planning should not only address the challenges posed by the invasion but also encompass adaptive measures to address these pressing climate change risks. Maintaining business-as-usual agricultural practices will not be enough in the face of these evolving conditions. The analysis highlights the growing necessity for irrigation to sustain crop production over the next 20-30 years, to prevent potential declines in agricultural productivity. In the context of increased water scarcity, efficient water management strategies and adopting more water-efficient practices will be key in building a more resilient and productive agriculture sector for the future. This will require addressing significant challenges within irrigation systems, such as their low efficiency and performance, energy and greenhouse gas emissions associated with irrigation water pumping, and deteriorating infrastructure. In future reconstruction plans, prioritizing efforts aimed at improving irrigation efficiency will be critical, reducing conveyance losses, and addressing the underutilization of existing irrigation infrastructure, in addition to the urgent need to expand critical irrigation services in areas facing GWS.

Opting for large-scale centralized irrigation systems could increase Ukraine's susceptibility to conflicts. It is advisable to embrace small-scale decentralized irrigation solutions like solar-powered drip irrigation to mitigate dependence on large-scale centralized systems prone to potential risks, as demonstrated by the damage to the Kakhovka reservoir. While smaller decentralized irrigation systems may be less prone to conflicts, vigilance is essential to prevent them from contributing to the depletion of natural resources. It is also imperative to consider cultivating drought-resistant crops that require minimal irrigation, a shift with the potential to reduce water demands and bolster agricultural resilience, improving crop water productivity by an average of 10%-30%. Additionally, land reform and incentives for on-farm investments will be crucial for promoting sustainable agriculture, attracting private investment, and preventing dilapidation of the irrigation infrastructure as happened after the collapse of the Soviet Union.

The results of this analysis clearly state that the urgency of action is evident. In rebuilding from the invasion, climate change impacts should also be considered. Climate change will exacerbate GWS and will make irrigation a necessity to maintain agricultural productivity, sustain livelihoods, and reduce poverty in Ukraine. Towards midcentury, Ukraine is expected to encounter green water scarcity impacting 25.5 million hectares of croplands. Over 18 million hectares of these croplands, sustainable irrigation expansion emerges as a viable adaptation strategy due to the availability of local surface and groundwater resources. Despite the ongoing invasion, it is crucial to recognize the urgency of preparing a recovery plan that not only focuses on rebuilding critically lost infrastructure but also on enhancing climate resilience against growing water stress for critical crops by sustainably expanding irrigation.

1. INTRODUCTION

Thanks to its fertile soils and extensive farmlands, Ukraine has firmly established itself as a prominent global producer and exporter of agricultural commodities (FAO, 2022). Before Russia’s invasion in 2022, Ukraine held the distinguished positions of being the world's fifth-largest wheat exporter, fourth-largest corn exporter, and third-largest rapeseed exporter (FAO, 2022). The agricultural sector played a pivotal role in the Ukrainian economy, contributing 11% to the gross domestic product, employing 20% of the workforce, and accounting for 40% of total exports prior to Russia’s invasion (USAID, 2022). The importance of Ukraine's robust and reliable agriculture sector in ensuring global food security cannot be emphasized enough.

Russia’s invasion has highlighted Ukraine's importance in global grain production and the potential impact on global food prices. The invasion has significantly disrupted agricultural activities, resulting in decreased productivity, and posing a threat to global food security (FAO, 2022). Additionally, the ongoing invasion of Ukraine has had a profound adverse impact on water resources and irrigation infrastructure (Shumilova et al., in 2023). According to estimates by a damage and needs assessment published by the World Bank in 2022, the damage to Ukraine's irrigation is roughly valued at US$190 million (World Bank, 2022). This extensive damage has had a tangible effect on agricultural output, leading to noticeable food shortages on a global scale (FAO, 2022; Bertassello et al., 2023). The countries most severely affected by these shortages are primarily situated in the Middle East and Africa (Abayi et al., 2022; Bertassello et al., 2023). Considering these developments, it is imperative to prioritize efforts aimed at addressing the invasion’s consequences and supporting the recovery of the agricultural sector in Ukraine. These actions are critical not only for alleviating global food shortages but also for maintaining stability in the global food market.

Irrigated agriculture plays a crucial role in agricultural practices and serves as an important adaptation strategy in the face of climate change (Rosa, 2022). As weather patterns become increasingly unpredictable and extreme, irrigation provides a means to mitigate the impacts of water scarcity on crop production (Rosa et al., 2020). By supplying water directly to crops, irrigation helps maintain soil moisture levels, supports plant growth, and ensures consistent yields even in challenging climatic conditions (Rosa et al., 2020). Additionally, increasing temperatures present a substantial danger to crop productivity and food security (IPCC, 2022). In fact, irrigation plays a crucial role to counteract the detrimental impacts of heat-stress on crops and maintain agricultural yields (Birthal et al., 2021; McDermid et al., 2023).

Less than 2% of Ukraine’s croplands were irrigated before the invasion (World Bank, 2022). Ukraine’s provision of irrigation services has experienced persistent challenges after the country gained independence from the Soviet Union in 1991. Initially developed for state-run farms, the irrigation system experienced fragmentation during the economic and political transition following the collapse of the Soviet Union in 1991. Consequently, the irrigated area in Ukraine has been dramatically impacted. In 2021 irrigated areas were just 15% of the total area equipped for irrigation in the Soviet era, significantly impacting rural livelihoods, climate resilience, food security, and economic development potential in the country. The low utilization of irrigation systems is attributable to poorly maintained and largely non-operational systems, and escalating energy costs with declining state funding (World Bank, 2022). Limited technical capabilities and insufficient funding for individual farms have resulted in irrigation systems falling into disrepair.

The limited irrigation capacity in Ukraine makes the country vulnerable to the impacts of global warming and threatens agricultural productivity. Irrigation is an insurance for farmers when rainfall fails, buffering crops against climate variability (Rosa, 2022). Most of Ukraine's exported crops rely solely on rainfall (or green water), and the effects of climate change on rainfed production remain uncertain. There is a lack of knowledge about how the combined crises of the invasion and climate change have impacted Ukraine's irrigated agriculture sector in the short, medium, and long-term. This knowledge gap hampers decision-making for agricultural adaptation and targeted investments in water resources and agriculture, hindering resilience and building back better in a post-invasion Ukraine.

In this analytical report, we quantify the impacts of climate change and Russia's invasion on irrigated agriculture in Ukraine. First, using remote sensing analysis validated with census data (State Agency for Water Resources, 2023), we assess the extent, performance, productivity, and water use of irrigated agriculture in Ukraine in the years preceding the invasion. Second, using remote sensing analysis we quantify the impacts on irrigation productivity and extent considering the impact of Russia's invasion on irrigation. Third, using earth systems models forced with historical and future climate conditions (He and Rosa, 2023), we quantify the impacts of prospective global warming on agricultural green water scarcity (GWS) in Ukraine (He and Rosa, 2023). Croplands face GWS when and where natural soil moisture is insufficient for optimal crop growth, necessitating irrigation to reduce water-stress and maintain agricultural productivity (Rosa et al., 2020). Finally, over croplands affected by GWS, we identify where water in rivers, lakes and aquifers will be locally available to meet irrigation water demand. By doing so, we quantify the potential of irrigation expansion to adapt agriculture to prospective GWS. Therefore, we identity regions in Ukraine where irrigation systems can be improved or expanded, facilitating a more resilient and sustainable agricultural sector. The findings can inform national-level water resources management policies, as well as guide infrastructure investment strategies in water storage and irrigation systems as part of the post-invasion reconstruction and recovery planning in Ukraine.

2. METHODS

We assessed the effects of climate change and Russia's invasion of Ukraine on country's irrigated agriculture. Firstly, we evaluated the status of irrigated agriculture in Ukraine and the impact of Russia's invasion on irrigation performance using remote sensing analysis. Additionally, we analyzed census data and remote sensing information to understand the extent and performance of irrigation in the years preceding the invasion, serving as a benchmark for post-invasion recovery efforts. Secondly, we employed earth systems models with current and future climate conditions to measure the potential consequences of global warming on both rainfed and irrigated agriculture, specifically focusing on the impacts of GWS on agricultural productivity. Lastly, using state-of-the-art hydrological models (Rosa et al., 2020), we identified areas where water resources are locally available to meet agricultural water demand and quantified the potential for sustainable irrigation expansion, which not only helps adapt to future GWS but also contributes to rebuilding and recovery efforts in the aftermath of the invasion, aligning with the principle of building back better as advocated by the World Bank (2022).

2.1 Data collection

We selected 20 irrigation schemes for the analysis of pre-invasion irrigation performance (Supplementary Table 1). We digitalized command areas using data from Ukraine's State Agency for Water Resources (State Agency for Water Resources, 2023). These 20 large irrigation schemes cover 60% of Ukraine's irrigated croplands, while the remaining 40% is served by small-scale irrigation schemes. Soybeans or maize are the most common irrigated crops (in terms of total irrigated crop area). Other dominant irrigated crops are sunflower and rapeseed. Irrigated maize, wheat & barley, and soybeans are cultivated in all schemes, and sunflower in all schemes except Bortnitska. These four dominant crops are therefore selected for assessing pre-invasion irrigation performance. Crop types, yields, and cropping calendars are taken from the census data on agricultural statistics of Ukraine for the years 2017-2021 (State Agency for Water Resources, 2023).

2.2 Water Accounting Tool

The water accounting tool web application is a Google Earth Engine (GEE) Application and allows access, visualization, summarizing and downloading crop-disaggregated annual maps of irrigated areas. The Application also provides access to crucial aggregate statistics for a user-selected year and area of interest (AoI). Statistics on the total cropped area and on the crop-specific water balance (precipitation P (mm), actual total evapotranspiration ET (mm), evaporation from precipitation ET green (mm)) are calculated for the corresponding AoI. Users can display high-resolution maps of crop types, irrigated area, evapotranspiration, biomass production and current and future GWS. The tool is accessible via a dedicated URL as a browser app in any internet browser. The app version presented here is configured to operate in Ukraine at the country level, and at the level of oblasts, rayons, and irrigation schemes: https://hydrosolutions.users.earthengine.app/view/cropmapper-ukr-demo

2.3 Assessment of green water scarcity

To determine GWS, we calculate the ratio between irrigation blue water requirements (BWR) or green water deficits, and crop water requirements (CWR). CWR represents the amount of water necessary for a crop to avoid water-stressed growth, while BWR is the amount of blue water needed by a crop to fulfill CWR in the absence of sufficient green water. When the soil moisture (green water) is unable to meet CWR, rainfed croplands experience GWS. Croplands are facing GWS when this ratio exceeds 0.4, indicating that the rainfall regime satisfies only 60% of CWR, resulting in a 40% water deficit for the crops. In such cases of water stress, crop yields tend to decrease, prompting farmers to utilize irrigation methods whenever possible. We define intermediate GWS when the GWS ratio is between 0.2 and 0.4; and GWS affected croplands when the GWS ratio is greater than or equal to 0.4. GWS is calculated for the period from April to September, aligning with Ukraine's typical irrigation season. This study does not evaluate the GWS of winter crops like wheat and barley, which begin their vegetation period before April.

2.4 Assessment of irrigation expansion potential

To evaluate the potential for irrigation expansion, we employed a methodology that involves identifying croplands experiencing GWS and currently lacking irrigation infrastructure (Rosa et al., 2020). The assessment is based on the ratio between total water consumption and renewable water availability, with a requirement that this ratio be less than 1. Renewable water availability is determined by considering both local runoff generation and upstream runoff, which together constitute blue water flows. These water flows encompass surface and subsurface runoff, i.e., water in rivers, lakes, and aquifers (Rosa et al., 2020). To calculate blue water flows, we utilized local runoff estimates and employed the upstream-downstream routing function in ArcGIS known as "flow accumulation." To protect environmental flows, which account for 60% of available runoff, we factor in environmental flow requirements (Rosa et al., 2020). Total water consumption encompasses irrigation water consumption or BWR, as well as water consumption from industrial and domestic activities as quantified by Hoekstra and Mekonnen (2012). Using the rainfed cropland extent from our 2017-2021 remote sensing analysis, we determined the potential for irrigation expansion in each pixel affected by GWS ($GWS \geq 0.4$). This assessment considered the local renewable water availability under different climate scenarios.

2.5 Climatic data for GWS and sustainable irrigation assessment

For each crop and scenario, we obtain crop water requirements (CWR) and blue water requirements (BWR) from He and Rosa (2023). These values are calculated using a crop water model (Chiarelli et al., 2020), which assesses CWR and BWR for 26 crop classes or 130 primary crops, representing 100% of global crop production. The model employs a daily time-step and a soil water balance approach during each crop growing season. CWR and BWR are determined based on precipitation and evaporation data under different climate conditions: baseline, 1.5°C, and 3°C climates. This assessment includes the baseline climate (1996-2005), as well as scenarios with a 1.5°C and 3°C increase in temperature (Figure 4). 3°C represents a plausible level of global expected by the end of the century under current policies, while 1.5°C represents the global target set in the Paris Agreement (Sognnaes et al., 2021; Pielke et al., 2022). The global mean temperature in 2022 was estimated to be 1.15°C above the average temperature of the late 19th century, from 1850 to 1900, a period often used as a preindustrial baseline for global temperature targets (WMO, 2020). The global mean temperature in the baseline period is estimated to be 0.6°C above the preindustrial era (WMO, 2022). The times when the three selected global climate models used in the study are projected to reach 1.5°C and 3°C climate conditions with respect to the preindustrial era are 2011-42 and 2047-86, respectively (Rosa et al., 2020). With the use of this framework, we accounted for model differences in transient response timing and standardize the response of various models to the same level of warming (Rosa et al., 2020). We also considered a Baseline scenario, defined as the period from 1996 to 2005, which aligns with the reference period for global crop distribution datasets.

For the baseline scenario (1996-2005 period), we use historical monthly observational climatic data sets. The potential reference evapotranspiration data with a resolution of $0.5° \times 0.5°$ is obtained from the University of East Anglia's Climate Research Unit Time Series (CRU TS version 4.01) (Harris et al., 2020). Precipitation data covering latitudes 50°N to 50°S at a resolution of $0.05° \times 0.05°$ is sourced from the CHIRPS data version 2.0 (Funk et al., 2015). Precipitation data for other latitudes is acquired from the National Oceanic and Atmospheric Administration's Climate Prediction Center Global Unified Gauge-Based Analysis of Daily Precipitation dataset, at a resolution of $0.5° \times 0.5°$ (Chen et al., 2008).

For future climate scenarios, we utilize monthly evapotranspiration, precipitation, runoff (surface and subsurface) outputs from three global climate models (GFDL-ESM2M, HadGEM2-ES, and MIROC-ESM-CHEM) and three hydrological models (LPJmL, H8, and WATERGAP2) from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) under the representative concentration pathway (RCP) 8.5 (Invasionszawski et al., 2014). RCP8.5 represents the highest emission scenario if greenhouse gas reduction efforts are not made. These models are selected to cover a range of wetter, average, and drier climate projections in terms of global precipitation patterns. We obtain 18 combinations of climate and hydrological model outputs, with nine for each of the 1.5°C and 3°C scenarios.

Both climate observations and future climate forcing data are downscaled to a 5 arcminute by 5 arcminute resolution to match the spatial scale of the MIRCA2000 crop species distribution data (Portmann et al., 2010). These downscaled data are then used to assess monthly irrigation BWR and CWR, which are subsequently used to evaluate agricultural GWS. The results are presented as the ensemble mean of the nine simulations for each scenario. The MIRCA2000 data set provides information on growing stages for the year 2000. We assess monthly GWS by averaging the results of 18 climate and hydrological model combinations under 1.5°C and 3°C scenarios. We do not account for the impact of severe droughts due to the use of a combination of monthly climate model outputs. This approach may not capture extreme events that occur on short periods, such as a daily timescale. GWS is evaluated on a grid cell basis using a 5 arcminute by 5 arcminute resolution, which is roughly equivalent to 10 kilometers at the equator. It is then refined to a 500-meter resolution using a morphological mean filter within 2-pixel square kernels (Figure 4).

3. Understanding the status of irrigated agriculture in Ukraine

We employed remote sensing methodologies to assess the precise extents of rainfed and irrigated agricultural lands in Ukraine, categorized by specific crops. Subsequently, we calculated actual evapotranspiration rates and conducted evaluations of biomass productions for both rainfed and irrigated croplands. This comprehensive approach allows for an examination of the state of rainfed and irrigated agriculture in Ukraine throughout the period spanning 2017 to 2022.

3.1 Pre-invasion irrigation extent

Utilizing remote sensing analysis cross-verified against census data (State Agency for Water Resources, 2023), our findings reveal that Ukraine’s overall irrigated cropped area remained relatively constant at 420,000 hectares, displaying annual fluctuations within a range of ±4% throughout the period spanning from 2017 to 2021 (Figure 1). Conversely, the average annual rainfed crop area encompasses approximately 25.27 million hectares (Mha), with yearly variances of ±4% (Figure 1). Consequently, a mere 1.6% of Ukraine’s agricultural land is under irrigation.

It is important to note that substantial regional variations and year-to-year fluctuations in irrigation water requirements exist. In Ukraine’s driest regions and during drought years, the consumption of irrigation water can escalate by up to 50% above the average values observed during the 2017-2021 period (Supplementary Figure S1). During the year 2021, the irrigation season experienced an exceptionally elevated amount of rainfall, nearly twice as much as during the years 2017-2020 (Supplementary Figure 2). Therefore, the discerned irrigated area was 9% lower than in the other years from 2017 to 2020 (Supplementary Figure 3). Irrigation infrastructure is fully concentrated in the southern oblasts of the country (Figure 1). Among these oblasts, Kherson led the way in 2021, boasting the largest irrigated area at 63% of the total. Zaporizhzhia followed closely behind with 16%, while Odesa, Mykolaiv, Crimea, and Dnipropetrovsk each accounted for 6%, 5%, 4%, and 4% of the irrigated areas, respectively.

In Ukraine, soybeans dominate as the most extensively irrigated crop, encompassing approximately 32% of the nation’s irrigated lands (Figure 1B). Sunflowers come in second at 18%, closely followed by maize at 16% (Figure 1B). The category of “wheat & barley,” encompassing various cereal crops, constitutes 22% of the irrigated area (Figure 1B). Notably, soybeans and maize together account for 56% of the total irrigation water usage (Figure 1C). Intriguingly, despite wheat & barley representing 22% of the total irrigated area, they consume only about 15% of Ukraine’s overall irrigation water volume, indicating their lower water intensity compared to maize and soybeans. On a national scale, our remote sensing analysis reveals that maize and soybeans necessitate approximately 240 mm and 260 mm of irrigation water annually, while wheat and barley require only around 160 mm per year. For irrigated soybeans and maize, roughly half of their water consumption is attributed to irrigation, with the remaining half sourced from rainfall (Figure 1D). In contrast, when it comes to irrigated wheat & barley, approximately 40% of their water intake is derived from irrigation, with the remaining 60% supplied by rainfall (Figure 1D). This underscores the fact that wheat & barley exhibit lower dependence on irrigation water compared to maize and soybeans, illustrating their reduced irrigation water intensity.

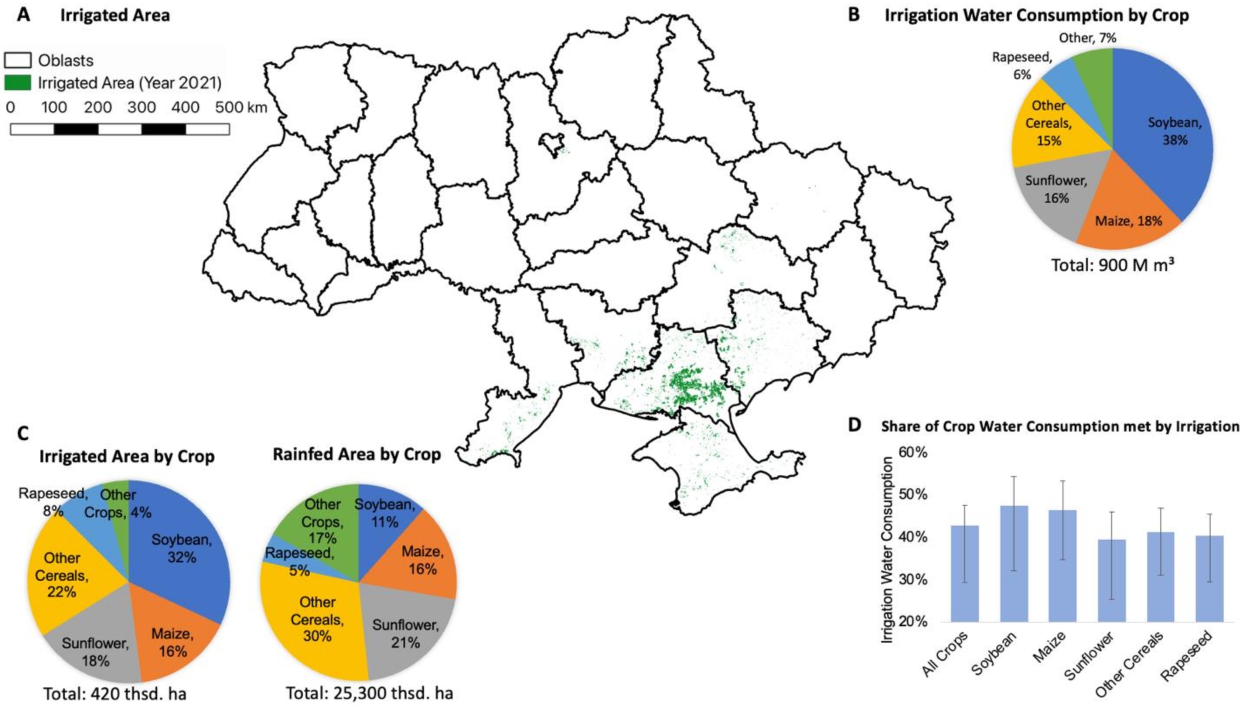


Figure 1. Irrigated area and water use in Ukraine in 2017-2021. (A) geospatial extent of irrigation in Ukraine; (B) irrigation water consumption by crop; (C) irrigated and rainfed cropped areas by crop; (D) fraction of crop water consumption met by irrigation; the values represent the average over the 2017-2021 period over irrigated areas of Ukraine. ‘Other Cereals’ mainly represent wheat & barley. ‘All Crops’ in panel D refers to the average over all irrigated areas. Interval bars reflect the annual variability in irrigation water consumption over total crop water requirements in 2017-2021.

3.2 Incremental yield from irrigation in 2017-2021

Prior to the invasion, our estimations indicate that irrigated crop yields surpassed rainfed yields by a notable 50% over approximately 80% of the irrigated croplands in Ukraine (Supplementary Figure 4). The extent of incremental yield varied depending on the specific irrigation scheme, with irrigated crops generally experiencing average yield enhancements ranging from 5% to as high as 80% compared to their rainfed counterparts (Supplementary Figure 4). Among all the cultivated crops, maize derived the greatest benefit from irrigation, demonstrating an average yield increase of 60% across all schemes (Supplementary Figure 4C). It is important to highlight that in the northern regions of Ukraine, irrigated croplands tended to show comparatively smaller incremental yields. This can be primarily attributed to the naturally higher yield of rainfed crops in these areas. This phenomenon is a result of cooler summer temperatures and increased rainfall in the northern regions, which inherently reduces the need for irrigation. As a result, in the northern regions, the average yield of irrigated crops in these regions did not significantly surpass that of rainfed crops.

3.3 Invasion impact on irrigation productivity

Ukraine relies on large-scale centralized irrigation systems, which are vulnerable targets during conflicts (Shumilova et al., in 2023). In addition, irrigated systems, relying on intricate infrastructure and coordinated water management, are more vulnerable to disruptions in invasion zones than rainfed systems, which have fewer dependencies on infrastructure and human coordination. As depicted in Supplementary Figure 8, marked drops in biomass production are predominantly evident within irrigation schemes, while areas outside these schemes show no comparable patterns. In 2022, we observed a noteworthy reduction of 56,000 hectares in the irrigated area compared to the average recorded between 2017 and 2021, constituting a 13% decrease in Ukraine’s total irrigated areas (Figure 2), after the invasion began in February 2022. The decline in irrigated areas can be primarily attributed to the fact that many irrigation systems are in regions either not under government control or affected by ongoing hostilities (Figure 2A). Notably, those irrigation schemes situated in areas with ongoing hostilities in August 2022 experienced some of the most substantial declines in irrigated areas, with reductions of up to 58% (Figure 2A). Conversely, regions farther away from the invasion zone did not witness a decrease in irrigated areas (Figure 2A).

Irrigated crop production has been adversely affected by Russia’s invasion of Ukraine. When compared to the average production levels from 2017 to 2021, agricultural productivity has significantly declined. Noteworthy reductions include a 65,000-tonne (t, metric tonnes) decrease (-14%) in maize production, a 120,000t decrease (-30%) in wheat and barley production, a 52,000t decrease (-17%) in soybean production, and a 36,000t decrease (-21%) in sunflower production (Figure 2C). These figures underscore the substantial challenges faced by irrigation schemes in maintaining agricultural productivity amid the ongoing invasion and territorial hostilities. Despite the invasion, irrigated regions consistently exhibit greater productivity than rainfed agriculture. The estimated productivity is 41% higher in 2022, a slight decrease from the 51% observed in the period from 2017 to 2021 (Supplementary Figure 10).

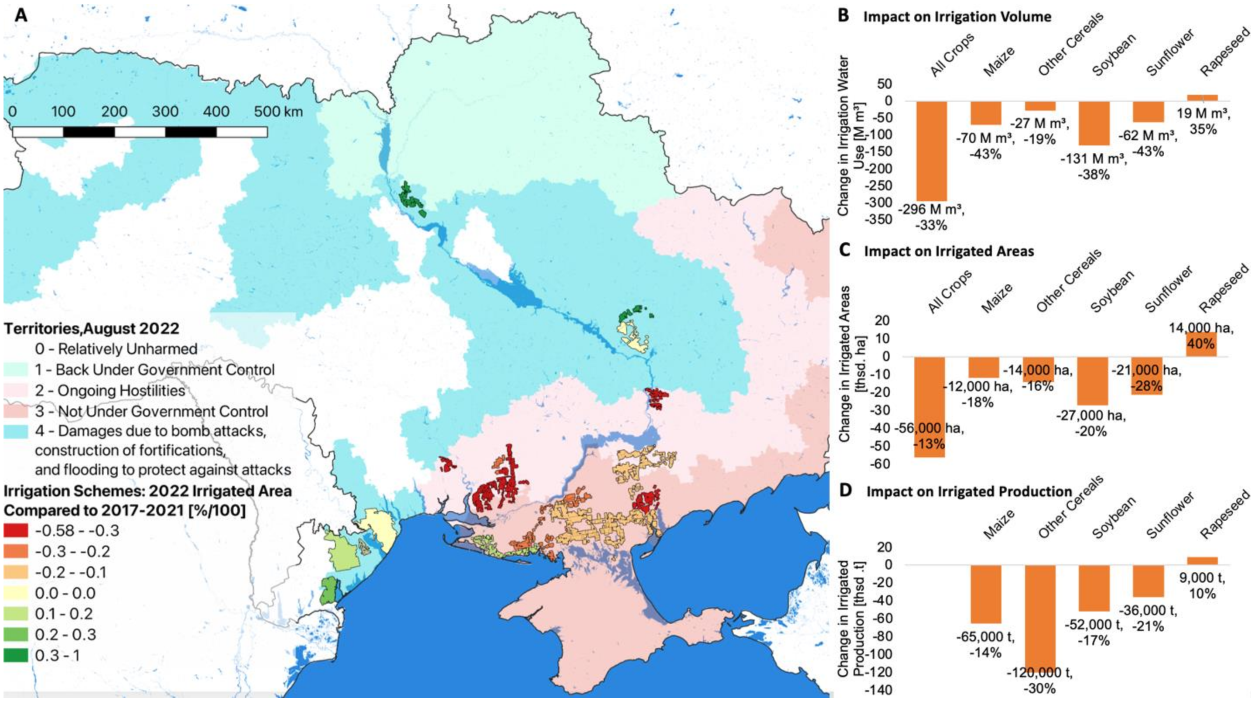


Figure 2. Impacts of invasion on irrigation productivity in Ukraine. Panel A shows the geospatial distribution of irrigation schemes and the impact of the invasion on irrigated areas. The invasion impact categories reflect the situation in August 2022 and do not represent the current situation, which is continuously evolving. Panels B, C and D illustrate changes in Ukraine's irrigation volume, areas, and production by crop in 2022 versus the 2017-2021 average. 'Other Cereals' mainly represent wheat & barley. 'All Crops' refers to the sum over all irrigated areas accounting also for other minor crops in addition to maize, wheat & barley, soybean, sunflower, and rapeseed. Our results for the 2017-2021 period versus 2022, show that rapeseed production increased by 10% (9,000 tons). This is because rapeseed is planted every 2-4 years during crop rotation and therefore with fluctuations in cultivated area and production up to 25% (State Agency for Water Resources, 2023).

3.4 Impact of Kakhovka dam collapse on irrigation

On the morning of June 6, 2023, a catastrophic event occurred as the Kakhovka reservoir dam collapsed, likely due to an explosion at the hydroelectric power station beneath it (Vyshnevskyi et al., 2023; TIME, 2023). This devastating incident resulted in the flooding of an area encompassing approximately 73,000 hectares (ICEYE Oy, 2023; Kourkouli, 2023). Urban areas along the Dnieper riverbanks suffered extensive damage as a direct consequence.

We assessed the damage caused by flooding using remote sensing layers of cropped area and the mapped extent of the flooded area. Our estimate shows that the impact on agricultural lands was relatively limited, affecting fewer than 150 hectares. Nevertheless, the repercussions on irrigated agriculture are anticipated to be severe. The Kakhovka reservoir served as the primary water source for several large-scale centralized irrigation systems in the southern region of Ukraine (Figure 3). According to our analysis, approximately 67% (±4) of Ukraine's pre-invasion irrigated areas, totaling 280,000 hectares, will be adversely affected due to the absence of water supply resulting from the complete destruction of the Kakhovka dam.

Of the affected irrigated area, approximately 85% (230,000 ha) was dedicated to the cultivation of crops with the primary irrigation season in July and August, predominantly soybeans, maize, and sunflower. The remaining 15% of the area was allocated to wheat & barley, whose primary irrigation season had already concluded at the time of the dam's destruction. If all irrigated crops transition to rainfed agriculture, we estimate production losses within the affected area to reach 30% for the year 2023, with projections indicating an increase to 36% in subsequent years, based on historical irrigation yield benefits.

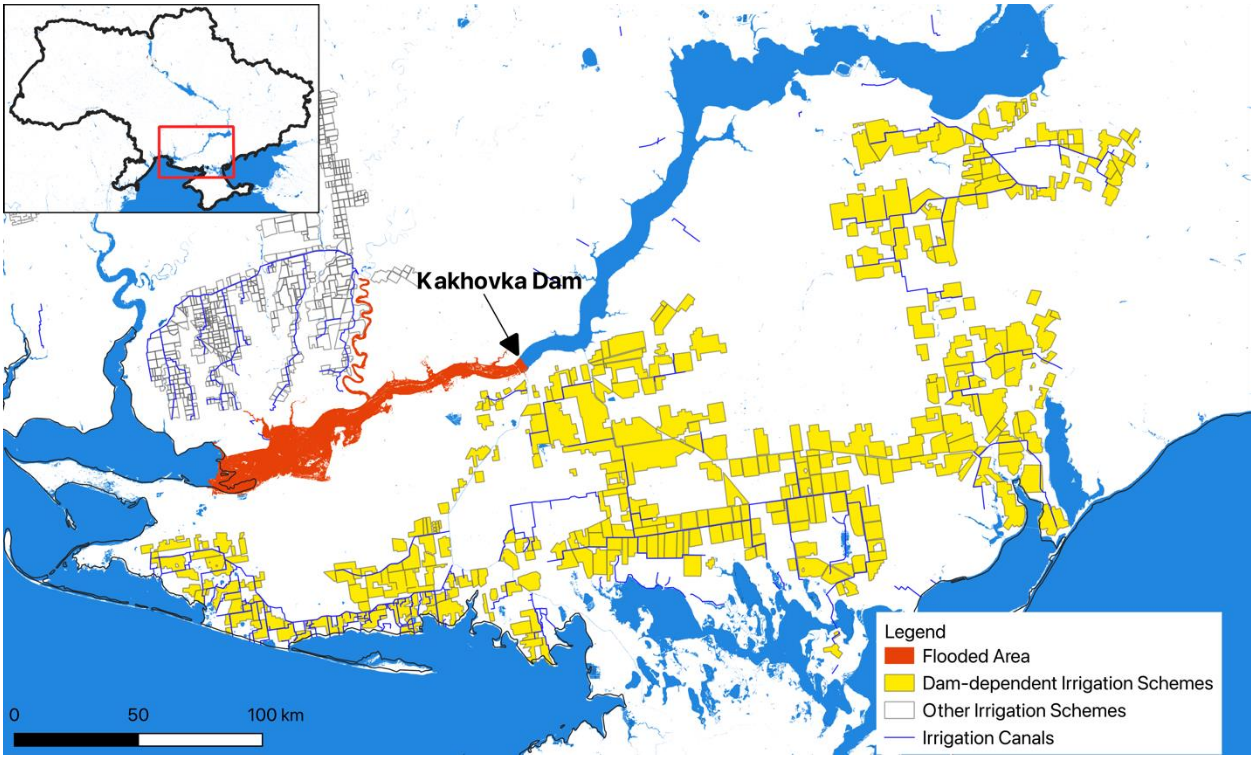


Figure 3. Impact of the Kakhovka Dam destruction on irrigated agriculture. The map shows the location of the Kakhovka Dam, the flooded area after destruction (ICEYE Oy, 2023), and the command areas of large irrigation schemes (>5000 ha) supplied by water from the Kakhovka reservoir (yellow). An inventory of irrigation canals was available to identify the water source of irrigation schemes (State Agency for Water Resources, 2023).

4.0 Understanding the impacts of climate change on the irrigation sector in Ukraine

4.1 Impacts of climate change on green water scarcity

While Russia's invasion of Ukraine has caused significant harm to irrigated agriculture in the recent years, climate change adverse impacts will continue to pose a threat to both rainfed and irrigated agricultural production system in Ukraine. We utilized climate data from the Coupled-Model-Intercomparison-Project (CMIP5) archive, obtained from earth system models, to evaluate croplands experiencing green water scarcity (GWS), where rainfall is insufficient for optimal crop growth, necessitating irrigation for increased yields. Firstly, the climate projections from CMIP5 (Warszawski et al., 2014) are inputted into a crop water model to evaluate crop water requirements and irrigation water requirements (He and Rosa, 2023). Secondly, crop water requirements and irrigation water requirements are used to assess GWS (He and Rosa, 2023). Thirdly, we quantify the extent of GWS, and the agricultural productivity impacts categorized by specific crops. This assessment includes the baseline climate (1996-2005), as well as scenarios with a 1.5°C and 3°C increase in temperature (Figure 4). 3°C warming represents a plausible level of global warming expected by the end of the century under current policies, while 1.5°C represents the global warming target set in the Paris Agreement (Sognnaes et al., 2021; Pielke et al., 2022).

In the baseline climate, without considering the impact of the invasion, we observe that 3.1 Mha, equivalent to ~10% of Ukraine's rainfed croplands, face GWS (Figure 4A). These croplands cannot achieve their maximum productivity due to water-stressed conditions. Specifically, Crimea, Odesa, and Kherson have 1.2 Mha, 1.1 Mha, and 0.8 Mha of rainfed croplands, respectively, experiencing a shortage of green water (Figure 5). The projected changes in temperature and precipitation patterns will further exacerbate GWS in the future (Figure 4B and C). With 1.5°C, an additional 10.4 Mha of rainfed croplands are expected to face GWS (41% in total croplands). Largest newly affected areas will be in Zaporizhzhia, Odesa, and Mykolaiv, with increases of +1.8 Mha, +1.7 Mha, and +1.0 Mha, respectively (Figure 5). With 3°C warming, another 12 Mha of rainfed croplands will face GWS. Therefore, with 3°C warming, 77% (or 25.5 Mha) of Ukraine's total cropland area will be affected by GWS. Dnipropetrovsk, Kirovohrad, and Kharkiv will experience the most significant increases in affected areas, with respective additions of +1.6 Mha, +1.6 Mha, and +1.1 Mha (Figure 5). The intensification of GWS poses a significant risk to agricultural productivity, especially in Southern Ukraine.

In the context of the baseline climate conditions, only 1% of Ukraine's total maize production, equivalent to 260 million metric tonnes (Mt), is cultivated in areas facing GWS (Figure 4E). However, if temperatures increase by 1.5°C and 3°C, assuming no alterations in crop patterns, the proportion of maize production exposed to GWS will rise to 13% (3.5 Mt) and 54% (15.6 Mt), respectively. For soybean production, the percentages affected by GWS is 1% under the baseline climate (0.10 Mt), 15% with a 1.5°C warming (1.1 Mt), and 53% with a 3°C warming (3.8 Mt). The crop most severely impacted by GWS is sunflower. Under the baseline climate, 5% of sunflower production (0.6 Mt) is affected, which increases to 40% (4.8 Mt) with a 1.5°C temperature rise and a staggering 82% (10.2 Mt) with a 3°C temperature increase (Figure 4). Interestingly, sunflower is a less thirsty crop compared to other typical irrigated crops like maize and soybean, requiring on average 20%-30% less irrigation water (Supplementary Figure 1). This lower water requirement is a key reason why, in Ukraine, sunflower is often cultivated as a rainfed crop, relying on natural rainfall patterns rather than irrigation systems.

In the 3°C warming scenario, the regions experiencing the most significant production declines for maize are Vinnytsia, Khmelnitsky, and Kirovohrad, with reductions of 2.1 Mt, 1.8 Mt, and 1.8 Mt, respectively. Similarly, for soybean, Khmelnitsky, Ternopil, and Poltava face reductions of 0.66 Mt, 0.37 Mt, and 0.36 Mt, respectively. For sunflower, Kharkiv, Kirovohrad, and

Dnipropetrovsk encounter substantial reductions of 1.5 Mt, 1.3 Mt, and 1.2 Mt, respectively (Supplementary Table 3).

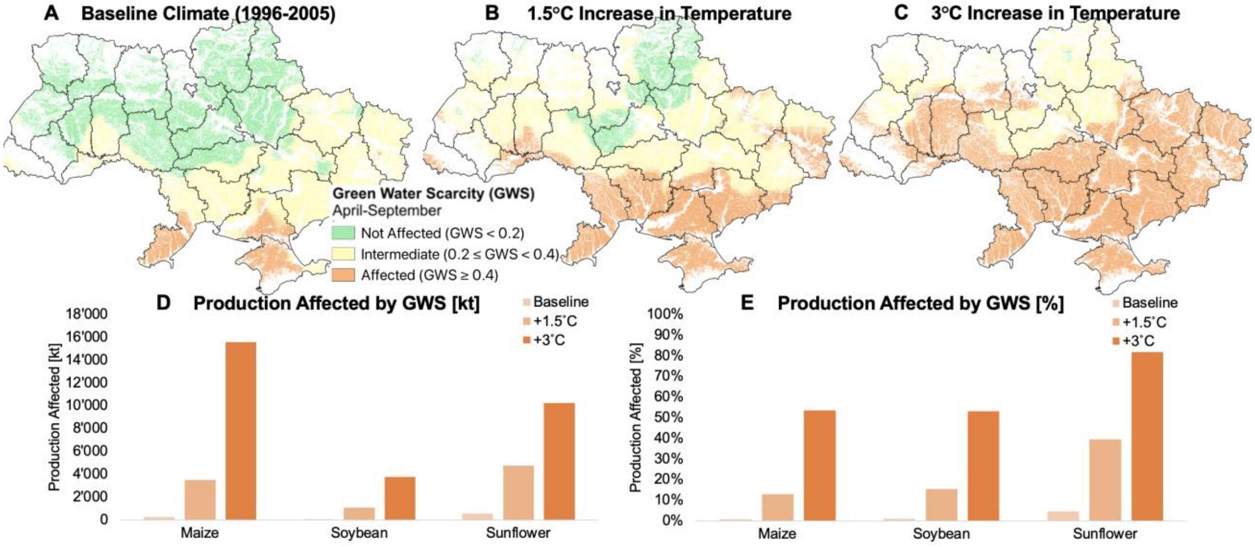


Figure 4. Geospatial extent of agricultural green water scarcity in Ukraine and impact on agricultural production. Maps A, B and C show GWS of cropland under baseline climate conditions, and under 1.5°C and 3°C warmer climates, respectively. Panels D and E show the corresponding total affected production of maize, soybean, and sunflower in units of thousand metric tonnes (kt), and as a fraction of the current total production, respectively.

4.2 Irrigation as an adaptation strategy climate change

To assess the potential for irrigation expansion under different climate scenarios, we utilized outputs from three earth system models in the CMIP5 archive (Warszawski et al., 2014). Our study focuses on identifying sustainable irrigation practices, which ensure that water consumption remains within local renewable water availability and does not harm environmental flows or deplete freshwater stocks (Rosa et al., 2019; Rosa et al., 2020). Over croplands experiencing GWS (Figure 4), we estimated the irrigation water requirements for rainfed croplands under baseline, 1.5 °C, and 3 °C warmer climate conditions. Finally, by examining renewable water availability, we mapped agricultural regions that have sufficient local surface water and groundwater resources for irrigation expansion. In essence, our approach identifies croplands where irrigation needs can be met using available renewable water resources (Rosa et al., 2020).

Under baseline climate conditions, approximately 60% (1.8 Mha) of cropland affected by GWS in Ukraine is suitable for sustainable irrigation expansion (Figure 5). Here, sustainable irrigation expansion is feasible because water is locally available to support agricultural production. It is important to note that further irrigation expansion is not sustainable in certain regions, namely in Odesa and Crimea (Figure 5). In these areas, irrigation practices deplete freshwater stocks in rivers, lakes, and aquifers, negatively impacting environmental flows. Environmental flows refer to the necessary quantity, timing, and quality of freshwater required to sustain freshwater ecosystems and their processes, as well as provide direct benefits to humans (Jägermeyr et al., 2017; Rosa et al., 2018).

Agricultural interventions implemented under current climate conditions are not going to be effective in the face of future global warming. Climate change is altering rainfall patterns, leading to more frequent and prolonged droughts, erratic precipitation events, and increasing evapotranspiration rates, which will worsen water scarcity over croplands in Ukraine. As a result, the total GWS affected cropland that is not suitable for sustainable irrigation expansion is projected to increase under warming scenarios. In a 1.5°C warmer climate, an additional 2.8 Mha (approximately 10% of the current total cropland area) will not be suitable for sustainable irrigation expansion. Namely, irrigation will become unsustainable over farmland in Kherson, Mykolaiv, Zaporizhzhia and Odesa oblasts (Figure 5, Supplementary Table 2). However, 69% (9.3 Mha) of the GWS affected cropland will be suitable for sustainable irrigation expansion (Figure 5).

Under a 3°C warmer climate, sustainable irrigation expansion will extend to areas further north. Nearly 18 Mha of cropland will be suitable for sustainable irrigation expansion, whereas 7.7 Mha will be affected by GWS without the possibility for sustainable irrigation water use. Under a 3°C warmer climate, oblasts where sustainable irrigation expansion is feasible are Crimea, Dnipropetrovsk, Donetsk, Kharkiv, and Kirovohrad (Figure 5). Agriculture in the south of Ukraine, but also in eastern and central Ukraine (see Figure 5) will be particularly challenged by water scarcity and strategic planning of adaptation strategies needs to be implemented to make agriculture sustainable and resilient in the coming decades.

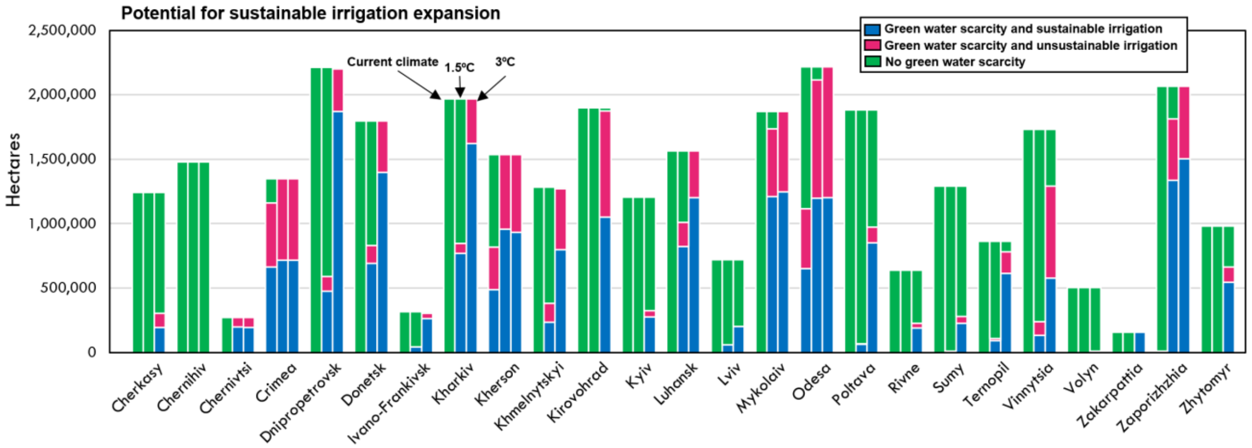


Figure 5. Potential for irrigation expansion in Ukraine under warming scenarios. The figure shows cropland areas per oblasts with and without green water scarcity under baseline, 1.5°C, and 3°C warmer climate. Areas facing green water scarcity are depicted considering the feasibility of sustainable irrigation expansion and the unsustainability of irrigation expansion under warming. Sustainable irrigation expansion is feasible when renewable water availability (surface plus groundwater) is locally available to meet irrigation water consumption (Rosa et al., 2020). Unsustainable irrigation is verified when irrigation water consumption depletes water resources in rivers, lakes and aquifers and impairs environmental flows. Supplementary Table 2 provides detailed quantitative data used to generate the figure. The figure considers areas suitable for sustainable irrigation expansion because water is locally available to meet demand and does not

consider irrigation systems and types of irrigation, such as large, centralized versus small, modular irrigation.

5.0 Building back better a climate resilient irrigation sector

To ensure effective planning for post-invasion rebuilding, it is essential to accurately quantify and fully comprehend the effects of the invasion and global warming on the irrigation sector. This study plays a crucial role in providing insights into the significance of irrigation in adapting and enhancing agricultural productivity in Ukraine amidst the challenges of warming temperatures. By establishing the groundwork, this study sets the stage for the development of strategies and interventions aimed at restoring and rehabilitating damaged irrigation infrastructure in a sustainable manner. It paves the way for effective planning and implementation of initiatives that will contribute to the long-term recovery and sustainability of irrigation systems, fostering the overall resilience and prosperity of the agricultural sector.

The findings of this analytical report underscore the fact that irrigation in Ukraine yields twice the productivity compared to rainfed agriculture. Prior to Russia's invasion, only 1.6% of Ukraine's cropland area benefited from irrigation. Unfortunately, our estimates indicate that a mere 27% of these irrigated areas have remained unaffected by the invasion. The Kakhovka dam played a pivotal role as the primary source of irrigation water in Southern Ukraine. Our analysis reveals that 67% of Ukraine's previously irrigated regions, amounting to 280,000 hectares, have experienced adverse effects due to the destruction of the Kakhovka dam, leading to a critical water supply shortage. Of these 280,000 hectares, 36,000 hectares were already lost the previous year during the invasion. As a result, we estimate that the cumulative loss of irrigated area totals 300,000 hectares. This represents 73% of the irrigated land present before the invasion.

Irrigation has the potential to significantly boost Ukraine's economy by enhancing agricultural production. Currently, irrigated crops yield double the productivity of rainfed agriculture, with a 50% increase in yields over 80% of irrigated croplands. Maize, a key export crop, experiences a notable 60% average yield increase with irrigation. This highlights the economic impact of expanded irrigation practices, providing a crucial opportunity to boost Ukraine's economy through increased production of essential crops. This increased production translates into higher incomes for food producers, with direct potential to reduce poverty, enhance livelihoods and well-being gains for farming families. This is critical to support Ukrainian farmers, who have suffered significant losses because of the invasion to their farms and investments. Irrigation also offers opportunities for additional job creation in rural communities as it creates employment in terms of skilled labor for system operation as well as unskilled labor for regular maintenance of systems, at all scales. Additionally, irrigation supports the cultivation of higher-value crops, such as vegetables, generating more income per unit of water compared to grain production. Given competition for water resources, adopting water- and energy-efficient irrigation systems post-invasion is crucial. Building back better with such systems could lead to greater service reliability, crop diversification, and higher-value cropping, offering substantial benefits through strategic investment in irrigation.

Climate change is adversely affecting Ukraine's agriculture, with increased frequency and severity of droughts, notably in 2020, causing a 12% decline in agricultural GDP (World Bank, 2022).

Effective adaptation involves improved water management and irrigation, acting as insurance for farmers during droughts. Southern Ukraine, cultivating key crops like corn and soybean, heavily depends on irrigation, which accounts for 56% of total irrigation water consumption. Irrigation is crucial for water-intensive crops, and climate-change models project sufficient water availability. Additionally, irrigation offers flexibility for farmers to shift to less water-intensive, higher-value crops. However, factors like market prices have a significant influence on farmers’ cropping choices, as well as access to markets and the appropriate value chains for farmers to sell their produce. Therefore, suggestions of optimal crop choices were out of the scope of this report. Overall, irrigated agriculture plays a pivotal role in mitigating water scarcity impacts by ensuring consistent yields in challenging climatic conditions.

The urgency of expanding irrigation in Ukraine is emphasized by the imminent threat of climate change, crucial for economic stability and global food security. Under baseline climatic conditions, approximately 10% of Ukraine’s rainfed croplands are susceptible to GWS. Rising temperatures and increased evaporation, particularly in the already arid southern region, lead to critical water shortages. This vulnerability poses a significant threat to agricultural productivity. With insufficient rainfall potentially affecting 41% and 77% of Ukraine's cropland under 1.5°C and 3°C global temperature increases respectively, expanding irrigation is vital for economic stability, food security, and employment. Cultivating drought-resistant crops like sunflower, barley, and wheat can reduce water demands and enhance agricultural resilience. Initiating necessary repair and adaptation efforts requires a long-term perspective, considering the anticipated increase in aridity in southern and eastern Ukraine.

Our climate change analysis indicates that continuing with business-as-usual agricultural practices is not advisable for Ukraine. As temperatures rise, the areas affected by GWS expand across all regions of the country. Without implementing effective water management strategies to address this issue, crop yields are expected to decline, reducing agricultural productivity, if agriculture continues to rely primarily on rain-fed sources. Consequently, there will be a growing need for irrigation to sustain crop production in the next 20-30 years. In the current baseline climate, 1.8 Mha of cropland in Ukraine, which is impacted by GWS, can be considered suitable for irrigation expansion. However, in a climate that has warmed by 1.5°C and 3°C, 69% (9.3 Mha) and 70% (18 Mha) of the cropland affected by GWS, respectively, will become suitable for sustainable irrigation expansion. Oblasts such as Dnipropetrovsk and Kharkiv should be prioritized for irrigation expansion because here water will be locally available to meet demand sustainably. However, it is crucial to carefully evaluate energy consumption and other local limitations when planning such initiatives to avoid unintended socio-environmental consequences (Rosa, 2022). Depending on the carbon intensity of energy, the additional energy use from irrigation expansion could lead to increases in carbon emissions if the inefficiencies are not adequately addressed.

Future challenges associated with water scarcity are likely to arise. Water infrastructure will need to be upgraded to store and transport larger quantities of water to meet the growing demand (Schmitt et al., 2022). This necessitates implementing more efficient water consumption practices in the agriculture sector. Furthermore, expanding the water supply is essential, ensuring that a significant area is not overly reliant on a single source (Di Baldassarre et al., 2019). The recent Kakhovka dam breach vividly illustrates the vulnerability of such a dependency and today questions remain whether the dam should be reconstruction, repurposed, or alternative solutions used. However, regardless of the decision, it is vital that the largest irrigation system in Europe have a reliable source of water to continue to feed millions of people around the world.

To overcome challenges in Ukraine's irrigation investment, addressing critical bottlenecks is essential. Large-scale centralized irrigation systems pose risks, as demonstrated by the damage to the Kakhovka reservoir. Opting for small-scale decentralized solutions like solar-powered drip irrigation can mitigate such risks. However, vigilance is needed to prevent these systems from contributing to natural resource depletion. The current centralized management of water and irrigation infrastructure is unsustainable, lacking clarity in institutional frameworks and incurring high energy costs. The vulnerability of large, publicly managed irrigation systems is evident, emphasizing the need for strategic reforms.

Our analysis shows that, prior to the invasion, irrigation systems faced efficiency issues, high energy costs, and deteriorating infrastructure, with the current system efficiency estimated at 25-30%, significantly below global best practices of 70-80% with sprinkler and drip irrigation (Supplementary Figure 4). This inefficiency results in the loss of more than half of the energy consumption for lifting water compared to established benchmarks. In the forthcoming reconstruction plans, it is imperative to prioritize efforts aimed at improving irrigation efficiency and reducing conveyance losses. This emphasis is particularly crucial for the Kakhovka scheme, which, until the invasion, held the distinction of being the largest scheme in both Ukraine and Europe (Reznik et al. 2016, Shumilova et al. 2023). Moreover, our findings indicate that there was an underutilization of existing irrigation infrastructure. This underutilization can be attributed primarily to the high energy costs associated with pumped irrigation systems and the deteriorating condition of the irrigation infrastructure.

The consequences of irrigation loss in Ukraine are not only significant for the country itself but also for the global community, as it can lead to major disruptions in global supply chains. The presence of an extensive network of irrigation channels in southern regions of Ukraine makes this issue particularly crucial. The poor quality of irrigation water has a direct impact on agricultural crops and the overall quality of food production (Zaman et al., 2018). Prior to the conflict, the concentrations of heavy metals in the waters of the Kakhovka Canal met the required water-quality standards (Khokhlova et al., 2019). However, there is concern that the ongoing conflict may lead to a deterioration in water quality, posing a potential threat to the agricultural sector. In fact, there is evidence of water pollution in reservoirs used for irrigation, which covers thousands of hectares in Ukraine (Shumilova et al., 2023). This is particularly worrisome since a significant portion of the harvested crops in Ukraine is intended for export purposes. The potential impact of such water pollution on the quality and safety of agricultural products could have far-reaching consequences for global trade and food security.

This study highlights the pressing need for immediate investment in rehabilitating and modernizing Ukraine's irrigation sector, which has suffered from years of neglect. The existing infrastructure is inadequate to meet the demands of the country's irrigated agriculture, particularly considering its transition to a market economy and integration into the European legislative framework (OECD, 2021). The collaborative effort in 2017, resulting in the Irrigation and Drainage Strategy, underscores a commitment to sector modernization and management reforms aimed at maximizing the net economic benefit from irrigated agriculture (Cabinet of the Ministers of Ukraine, 2019). A pivotal reform involves decentralizing the irrigation sector by entrusting management responsibilities to local stakeholders through Water Users' Organizations. While crucial for sector advancement, implementing this reform presents substantial challenges, necessitating comprehensive efforts to address institutional and legal issues for the successful establishment of Water Users' Organizations. The study's findings on the nature, distribution, and potential impacts of the invasion and global warming on irrigated agriculture lay a foundation for future reconstruction and restoration efforts, emphasizing the importance of sustainability, equity, and environmental conservation in the rehabilitation process.

6.0 Caveats

Several critical aspects should be considered in future work to provide a more comprehensive understanding of irrigation dynamics. Firstly, there is a need to delve into the proportion of irrigated production allocated for domestic use versus export, shedding light on the economic dimensions of irrigation. Another crucial factor is the evaluation of energy and carbon emissions associated with irrigation, recognizing that cost limitations, primarily stemming from energy use, play a significant role in shaping irrigation practices.

The distinction between groundwater and surface water sources emerges as a key consideration. Future studies should explore farmers' access to these water sources, including the depth of groundwater, its feasibility for pumping, and the associated economic and energy costs. Improved mapping of groundwater systems is imperative for a more accurate assessment.

The choice between large, centralized infrastructure and small modular systems, such as solar drip irrigation, requires a nuanced analysis. This involves identifying regions where each approach is better suited, considering social factors alongside technical feasibility. Additionally, the impact of irrigation on farming practices in a warming climate, including the potential for double cropping and the selection of optimal crops, should be a focal point of future investigations. Moreover, an in-depth analysis incorporating climate extremes, beyond average multi-model simulations, is crucial for a more robust understanding of the challenges and opportunities associated with irrigation expansion. These avenues of inquiry will contribute to a more nuanced and actionable framework for sustainable irrigation development.

Together, these analyses will offer a holistic understanding of Ukraine's water sector challenges, offering guidance for recovery investments and promoting improved water management practices to foster sustainable development in the aftermath of the invasion.

Annex 1. Data collection & assessment of crop type and irrigated areas via remote sensing

Crop type

We use satellite imagery to provide information on cropped and irrigated areas, crop types, and vegetation periods. The basis for the annual crop maps used in this study is a detailed 10-m Ukraine crop and land cover map available for the year 2019 (Deininger et al., 2023). This map was built using 2481 training samples of winter and summer crops collected in 17 oblasts during the year 2019, and a convolutional neural network to classify land cover and crop types based on optical data from Sentinel-2 and SAR data from Sentinel-1 (Deininger et al., 2023; Kussul et al., 2017). To generate annual crop maps for the 2017-2022 period, we first randomly sample 200 pixels from every crop and land cover type in the 2019 base map (18 types in total, including also non-crop types such as artificial areas, forest, grassland, bare land, wetlands, and low trees). A Random Forest classifier is then trained on March to September Sentinel-2 15-day composites (NDVI, Blue, Green, short wave infrared (SWIR1) and SWIR2 bands) and is subsequently applied to reclassify all pixels for each year 2017-2022 (Luo et al., 2022). The sampling and reclassification of pixels is performed separately for every region of Ukraine (24 oblasts and the autonomous republic of Crimea). The land cover types not representing annual crops are then removed from the maps. In addition, we use the annual layers of the Copernicus Global Land Cover Layers (CGLS-LC100 collection 3) (Buchhorn et al. 2020) product to obtain masks of cropped areas. Pixels with a ‘crops-cover fraction’ equal to zero and an ‘urban-cover fraction’ of greater than 90% are excluded from the masks.

Cropland Area

The cropland area of Ukraine was obtained by mosaicking the annual cropped area maps. 'Cropland' refers to all areas used for the cultivation of annual crops over the six-year observation period from 2017 to 2022.

Irrigated Area

To map irrigated areas, we employed a Random Forest classifier, utilizing 15-day composite images from Sentinel-2. We manually selected training pixels through the photointerpretation of center-pivot irrigation schemes. For each oblast with irrigation systems, and each year 2017-2022, we sampled 50 training pixels from within the center-pivots and another 50 from the surrounding rainfed cropped areas. The Random Forest classifiers were then used to determine the irrigation status for each cropped pixel of each year 2017-2022. Pixels identified as irrigated in fewer than 2 of the 6 years were excluded from the final irrigated area map. Additional post-processing steps involve the use of monthly actual evapotranspiration maps and a water balance approach. Details are provided in the section below.

Actual Evapotranspiration

High resolution daily actual evapotranspiration (ET_a) data for the days of Landsat acquisitions from the United States Geological Service (USGS) is used in this study to calculate (ET_a (Senay et al., 2023). Landsat Collection 2 Provisional ET_a products are generated by solving the surface energy balance equation for the latent heat flux using the Operational Simplified Surface Energy Balance (SSEBop) mode (Senay et al., 2018). This product uses the Landsat C2 Level-2 Surface Temperature (LST) as input to a SSEBop model with external auxiliary data to retrieve the daily total of ET_a (Senay et al., 2023). LST is derived from Landsat thermal satellite imagery, which detects naturally emitted radiation in the infrared portion of the spectrum. The daily ET_a maps are pre-processed to remove errors and fill in gaps and are then aggregated to monthly (ET_a) maps with a spatial resolution of 30 meters.

The available ET_a data is used to estimate green and blue water consumption based on the maps of rainfed and irrigated crops. Green evapotranspiration (ET_{GREEN}) (non-irrigation water) is equivalent to actual evapotranspiration (ET_a) over rainfed agricultural land (Karimi et al, 2019). ET_{GREEN} is first calculated on a monthly scale and ET_{GREEN} and ET_a are then summed over the vegetation period of every cropped pixel (see the section below on vegetation periods). Blue evapotranspiration (ET_{BLUE}) (irrigation water) is then calculated using a water balance approach:

$$ET_{BLUE} = \max\left(ET_a - ET_{GREEN}, 0\right) \tag{1}$$

The water balance approach is applied to every 10-meters grid cell of the annual cropped area maps in an iterative approach. First, the cropped area maps and the initial irrigated area maps are used as an input to obtain seasonal maps of ET_{GREEN} and ET_{BLUE}, respectively. The resulting maps of ET_{BLUE} are then used to post-process the irrigated area maps: pixels initially classified as irrigated with ET_{BLUE} equal to zero are reclassified as rainfed, and pixels initially classified as rainfed with ET_{BLUE} larger than 150 mm are reclassified as irrigated. The value of 150 mm is chosen based on empirical data from the south of Ukraine. The resulting final irrigated area maps are used as an input for a second iteration of ET_{GREEN} and ET_{BLUE} calculations. The resulting maps of seasonal ET_{BLUE} provide the estimates of crop irrigation water consumption.

Above Ground Biomass Production Maps

To calculate seasonal biomass production and crop yield estimates, we use the dry matter Productivity (DMP) product downloaded from the Copernicus Global Land Service (https://land.copernicus.eu/global/products/dmp). The product is available at a spatial resolution of 300 meters for 10-day intervals, starting in January 2014 (Chevuru et al., 2023). The decadal DMP is aggregated into monthly layers (unit kg/ha/month) and then converted into yields of major crops based on typical harvest indices (HI) and moisture content M:

$$Yield = \frac{AGBP \times HI}{1-M} \tag{2}$$

Where yield is in kg/ha and $AGBP$ is above ground biomass production in kg/ha (Safi et.al., 2022). Using average Census yield data from 2017 to 2021 (State Agency for Water Resources, 2023), we calibrated the harvest indices separately for maize, winter cereals, sunflower, soybean, and rapeseed for every Oblast of Ukraine. The resulting crop yield estimates are used to calculate key indicators for irrigation performance (water productivity and incremental yield) and to estimate the agricultural production threatened by GWS under different climate scenarios.

Vegetation Periods and Cropping Intensity

The generation of maps of vegetation periods and cropping intensity is based on the analysis of the Normalized Difference Vegetation Index (NDVI) (Pettorelli et al., 2005; Huang et al., 2021). NDVI is the normalized difference between red and the near-infrared spectral reflectance measurements (in our case provided by Sentinel-2 15-day composite images). NDVI of an area containing dense vegetation tends to a value of about 0.3 to 0.8. A time-series analysis of 15-day NDVI then allows to identify the vegetation period and the number of crops planted and harvested per year ('cropping intensity'). The vegetation period is defined as starting one month prior to NDVI reaching above 0.3 and ends when NDVI drops again below this value. The results of the analysis are annual maps of vegetation periods and cropping intensity with a spatial resolution of 10 meters. The maps are subsequently used for a detailed analysis of ET_a or $AGBP$ of crops over their actual vegetation periods. The cropping Intensity is used as an indicator of irrigation performance. In our remote sensing analyses, wheat and barley are not differentiated because of their phenology (e.g., NDVI signature) is very similar and the applied remote sensing techniques cannot differentiate the crops (Huang et al., 2022).

Other datasets

The analysis of precipitation patterns is based on Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) Version 2.0 data, which is a dataset that combines satellite observations with global models and measurements at local stations (Funk et al, 2015). The dataset provides daily total precipitation (in mm) at resolution of approximately 5 km (0.05°).

Validation of remote sensing analyses of irrigated agriculture

Supplementary Figure 5 and 6 illustrate the comparison between official statistics on irrigated and cropped areas, respectively, and remote sensing data. Among these oblasts, Kherson has the largest irrigated area, which amounts to around 0.26 million hectares according to both the State Agency for Water Resources (State Agency for Water Resources, 2023) and remote sensing data. According to census data (State Agency for Water Resources, 2023), the key irrigated crops include soybeans, cereals (mainly wheat and barley), maize, sunflower, and rapeseed. The fraction of irrigated area represented by these five crop categories is shown in Supplementary Figure 7. We compare only the fractions of irrigated area because the available census data on irrigated areas by crop type only represent part of the total irrigated area of Ukraine. The census data presented in Supplementary Figure 7 represent only the agricultural areas managed by enterprises. It does not include data from households, which in Ukraine account for about 30% of the cultivated agricultural area (State Agency for Water Resources, 2023). Additionally, census data from Crimea is not available. Nevertheless, despite these limitations, the comparison reveals a strong correspondence between the typical distribution of irrigated crops and the findings from the remote sensing analysis. According to both datasets, soybeans emerge as the most irrigated crop. Remote sensing data tends to underestimate the fraction of irrigated area represented by 'other crops' (including fodder, peas, potatoes, vegetables, fruits, berries, and grapes). The reason for this is that training data for irrigated crops representing only very small fractions of the total irrigated area are lacking. Such crops therefore tend to be classified as rainfed or they are associated with one of the main irrigated crop classes. These findings highlight the importance of considering both census data and remote sensing data to obtain a more accurate understanding of irrigated crop areas.

REFERENCES

Abay, K.A., Breisinger, C., Glauber, J., Kurdi, S., Laborde, D. and Siddig, K., 2023. The Russia-Ukraine war: Implications for global and regional food security and potential policy responses. Global Food Security, 36, p.100675.

Birthal, P.S., Hazrana, J., Negi, D.S. and Pandey, G., 2021. Benefits of irrigation against heat stress in agriculture: evidence from wheat crop in India. Agricultural Water Management, 255, p.106950.

Bertassello, L., Winters, P. and Müller, M.F., 2023. Access to global wheat reserves determines country-level vulnerability to conflict-induced Ukrainian wheat supply disruption. Nature Food, 4(8), pp.673-676.

Buchhorn, M., Smets, B., Bertels, L., De Roo, B., Lesiv, M., Tsendbazar, N.E., Herold, M. and Fritz, S., 2020. Copernicus global land service: Land cover 100m: collection 3: epoch 2019: Globe. Version V3. 0.1., https://doi.org/10.5281/zenodo.3518038

Cabinet of the Ministers of Ukraine, 2019. On the approval of the Irrigation and Drainage Strategy in Ukraine for the period up to 2030. Available at: https://zakon.rada.gov.ua/laws/show/688-2019-%D1%80#Text. Accessed: September 2023.

Chen M, et al. 2008. Assessing objective techniques for gauge-based analyses of global daily precipitation. J Geophys Res Atmos. 113(D4).

Chevuru, S., de Wit, A., Supit, I. and Hutjes, R., 2023. Copernicus global crop productivity indicators: An evaluation based on regionally reported yields. Climate Services, 30, p.100374.

Chiarelli, D.D., Passera, C., Rosa, L., Davis, K.F., D'Odorico, P. and Rulli, M.C., 2020. The green and blue crop water requirement WATNEEDS model and its global gridded outputs. Scientific data, 7(1), p.273.

Di Baldassarre, G., Wanders, N., AghaKouchak, A., Kuil, L., Rangecroft, S., Veldkamp, T.I., Garcia, M., van Oel, P.R., Breinl, K. and Van Loon, A.F., 2018. Water shortages worsened by reservoir effects. Nature Sustainability, 1(11), pp.617-622.

Deininger, K., Ali, D. A., Kussul, N., Shelestov, A., Lemoine, G., and Yailimova, H., 2023. Quantifying war-induced crop losses in Ukraine in near real time to strengthen local and global food security. Food Policy, 115, 102418.

Environmental impacts of the invasion in Ukraine and prospects for a green reconstruction. OECD (1 Jul 2022); https://go.nature.com/3XBfX0J

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. and Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Scientific data, 2(1), pp.1-21.

Harris I, Osborn TJ, Jones P, Lister D. 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci Data. 7:1–18.

He, L. and Rosa, L., 2023. Solutions to agricultural green water scarcity under climate change. PNAS nexus, 2(4), p.pgad117.

Hoekstra, A.Y. and Mekonnen, M.M., 2012. The water footprint of humanity. Proceedings of the national academy of sciences, 109(9), pp.3232-3237.

Huang, S., Tang, L., Hupy, J.P., Wang, Y. and Shao, G., 2021. A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. Journal of Forestry Research, 32(1), pp.1-6.

Huang, X., Fu, Y., Wang, J., Dong, J., Zheng, Y., Pan, B., Skakun, S. and Yuan, W., 2022. High-resolution mapping of winter cereals in Europe by time series landsat and sentinel images for 2016–2020. Remote Sensing, 14(9), p.2120.

ICEYE Oy., 2023. Flooded areas following the destruction of the Kakhovka dam (dataset). ICEYE Oy Satellite Data.

IPCC 2022 Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change ed H O Pörtner et al (Cambridge: Cambridge University Press) Climate change 2022: impacts, adaptation, and vulnerability (available at: www.ipcc.ch/report/ar6/wg2/about/how-to-cite-this-report/

Jägermeyr, J., Pastor, A., Biemans, H. and Gerten, D., 2017. Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. *Nature communications*, *8*(1), p.15900.

Karimi, P., Bongani, B., Blatchford, M., de Fraiture, C., 2019. Global Satellite-Based ET Products for the Local Level Irrigation Management: An Application of Irrigation Performance Assessment in the Sugarbelt of Swaziland. Remote Sens.,11, pp 705.

Khokhlova, L. and Lukashev, D, 2019. Assessment of heavy metal contamination of the technoecosystem of the Kakhovka main canal of the Kakhovka irrigation system. Environ. Probl. 4, 197–202.

Kourkouli, P., 2023. Natural disaster monitoring using ICEYE SAR data. In Geoinformatics for Geosciences, Chapter 9 (pp. 163-170), Elsevier. https://doi.org/10.1016/B978-0-323-98983-1.00010-7.

Kussul, N., Lavreniuk, M., Skakun, S. and Shelestov, A., 2017. Deep learning classification of land cover and crop types using remote sensing data. IEEE Geoscience and Remote Sensing Letters, 14(5), pp. 778-782.

Luo, Y., Zhang, Z., Zhang, L., Han, J., Cao, J. and Zhang, J., 2022. Developing high-resolution crop maps for major crops in the 25uropean union based on transductive transfer learning and limited ground data. Remote Sensing, 14(8), p.1809.

McDermid, S., Nocco, M., Lawston-Parker, P., Keune, J., Pokhrel, Y., Jain, M., Jägermeyr, J., Brocca, L., Massari, C., Jones, A.D. and Vahmani, P., 2023. Irrigation in the Earth system. Nature Reviews Earth & Environment, pp.1-19.

OECD (2021), Developing a Water Policy Outlook for Georgia, the Republic of Moldova and Ukraine, OECD Studies on Water, OECD Publishing, Paris, https://doi.org/10.1787/512a52aa-en.

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J. and Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends in ecology & evolution, 20(9), pp.503-510.

Pielke Jr, R., Burgess, M.G. and Ritchie, J., 2022. Plausible 2005-2050 emissions scenarios project between 2 and 3 degrees C of warming by 2100. *Environmental Research Letters*.

Portmann, F.T., Siebert, S. and Döll, P., 2010. MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. Global biogeochemical cycles, 24(1).

Ragettli, S., Sinha, R., Karimi P., Zhovtonog O., Danilenko, J., Rosa, L., 2023. cropmapper-ukr-demo [Google Earth Engine Application]
https://hydrosolutions.users.earthengine.app/view/cropmapper-ukr-demo

Reznik, V. S., Morozova, O. S., Morozov, O. V., Jaskulska, I. & Kamieniarz, J. Current state of irrigation in the Kherson steppe zone of Ukraine and in Kujawsko–Pomorskie province in Poland. Acta Sci. Pol. Agric. 15, 73–83 (2016).

Rosa, L., 2022. Adapting agriculture to climate change via sustainable irrigation: Biophysical potentials and feedbacks. Environmental Research Letters, 17(6), p.063008.

Rosa, L., Chiarelli, D.D., Rulli, M.C., Dell'Angelo, J. and D'Odorico, P., 2020. Global agricultural economic water scarcity. Science Advances, 6(18), p.eaaz6031.

Rosa, L., Chiarelli, D.D., Sangiorgio, M., Beltran-Peña, A.A., Rulli, M.C., D'Odorico, P. and Fung, I., 2020. Potential for sustainable irrigation expansion in a 3 C warmer climate. Proceedings of the National Academy of Sciences, 117(47), pp.29526-29534.

Rosa, L., et al., (2021). Energy implications of the 21st century agrarian transition. Nature communications, 12(1), 2319.

Rosa, L., Rulli, M.C., Davis, K.F., Chiarelli, D.D., Passera, C. and D'Odorico, P., 2018. Closing the yield gap while ensuring water sustainability. *Environmental Research Letters*, *13*(10), p.104002.

Safi, A.R., Karimi, P., Mul, M., Chukalla, A. and De Fraiture, C., 2022. Translating open-source remote sensing data to crop water productivity improvement actions. Agricultural Water Management, Vol. 261, 107373.

Senay, G. B. (2018). Satellite psychrometric formulation of the Operational Simplified Surface Energy Balance (SSEBop) model for quantifying and mapping evapotranspiration. Applied engineering in agriculture, 34 (3), 555-566. https://doi.org/10.13031/aea.12614

Senay, G.B., Parrish, G.E., Schauer, M., Friedrichs, M., Khand, K., Boiko, O., Kagone, S., Dittmeier, R., Arab, S. and Ji, L., 2023. Improving the Operational Simplified Surface Energy Balance Evapotranspiration Model Using the Forcing and Normalizing Operation. Remote Sensing, 15(1), p.260.

Shumilova, O., Tockner, K., Sukhodolov, A., Khilchevskyi, V., De Meester, L., Stepanenko, S., Trokhymenko, G., Hernández-Agüero, J.A. and Gleick, P., 2023. Impact of the Russia–Ukraine armed conflict on water resources and water infrastructure. Nature Sustainability, pp.1-9.

Schmitt, R.J., Rosa, L. and Daily, G.C., 2022. Global expansion of sustainable irrigation limited by water storage. Proceedings of the National Academy of Sciences, 119(47), p.e2214291119.

Sognnaes, I., Gambhir, A., van de Ven, D.J., Nikas, A., Anger-Kraavi, A., Bui, H., Campagnolo, L., Delpiazzo, E., Doukas, H., Giarola, S. and Grant, N., 2021. A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. *Nature Climate Change*, *11*(12), pp.1055-1062.

State Agency for Water Resources, 2023. Available at: https://www.ukrstat.gov.ua/. Accessed: September 2023.

The Importance of Ukraine and the Russian Federation for Global Agricultural Markets and the Risks Associated with the War in Ukraine (FAO, 10 June 2022); https://www.fao.org/3/cb9013en/cb9013en.pdf

TIME, 2023. https://time.com/6285811/ukraine-kakhovka-dam-bombing-impact-essay/ (website, accessed on 30 June 2023)

USAID. 2022. Agriculture Fact Sheet Ukraine. Available at: https://reliefweb.int/report/ukraine/agriculture-fact-sheet-enuk. Accessed: June 2023.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O. and Schewe, J., 2014. The inter-sectoral impact model intercomparison project (ISI–MIP): project framework. Proceedings of the National Academy of Sciences, 111(9), pp.3228-3232.

World Bank 2022 Water in agriculture (available at: www.worldbank.org/en/topic/water-in-agriculture#1) (Accessed May 2023)

World Bank. 2022. Ukraine rapid damage and need assessment- August 2022. Available at: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099445209072239810/p17884304837910630b9c6040ac12428d5c. Accessed: June 2023.

World Meteorological Association, State of the Global Climate 2021. 2022.

Zaman, M., Shahid, S.A., Heng, L., Zaman, M., Shahid, S.A. and Heng, L., 2018. Irrigation water quality. Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques, pp.113-131.

SUPPLEMENTARY MATERIALS

Assessment of pre-invasion irrigation performance

We focus on the top 20 irrigation systems (Figure 2), which rely on major infrastructure to distribute water from rivers or reservoirs (Supplementary Table 1). To conduct our irrigation performance analysis, we evaluate five key indicators, namely cropping intensity, scheme utilization, crop water productivity, incremental yield, and irrigation efficiency (Supplementary Figure 4).

Cropping intensity

The cropping intensity metric measures the frequency of harvests per year per irrigated pixel. We observed a cropping intensity that varies between 100% (only one harvest per year) and 121% (two harvests per year on 21% of the irrigated area), depending on the specific year and scheme. The average cropping intensity over all irrigated areas of Ukraine in 2017-2021 is 110%. For 13 out of the 20 irrigation schemes, the average cropping intensity from 2017 to 2021 is below 105% (Supplementary Figure 4B). The irrigation water demand of double cropping exceeds the irrigation water demand of single crop rotations on average by 35% (24%-44%, or 50-100 mm, Supplementary Figure 1). Nonetheless, transitioning from single to double cropping requires less additional irrigation water than expanding the irrigated area, which would need an extra 140-230 mm on average.

Scheme Utilization

Scheme utilization refers to the proportion of an irrigation system's command area that is effectively utilized. Our remote sensing analyses show that large irrigation systems with command areas exceeding 50,000 hectares predominantly employ center pivots for sprinkler irrigation. Areas beyond the coverage of center pivots systems mostly rely on rainfed agriculture. However, this factor only partially explains the low scheme utilization values we have observed. Except for Sirogozka (with an average utilization rate of 68%) and Kakhovka (47%), all other schemes exhibit an average utilization of less than 25% of the command area (Supplementary Figure 4A). The primary contributing factors to this underutilization are the high energy costs associated with pumped irrigation systems and the deteriorating condition of the irrigation infrastructure.

Crop water productivity

Crop water productivity measures the average yield of irrigated crops per unit of water consumed. Yields for irrigated soybeans, maize, sunflower, and wheat & barley are divided by the average evapotranspiration during the growing season to calculate crop water productivity in kg/m^3 for each crop in each scheme where the crop is present. Crop water productivity of the different crops show high spatial and temporal variability across and within the studies schemes in Ukraine. Oleksandrivska, Chaplynska and Kakhovka (all in Kherson oblast) have the highest crop water productivities for maize, but their crop water productivity regarding sunflower is close to the average of all schemes (Supplementary Figure 4D). Priazovska (Zaporizhzhia oblast) and Inguletska (Kherson oblast) obtain for all crops values that are below the average of all schemes. Soil conditions may explain the differences in crop water productivity to some degree. However, the highest value among all schemes can serve as a ‘best practice’ benchmark. By this measure, pre-invasion crop water productivity could be improved by an average of 10%-30%, varying by crop type. The greatest potential for productivity gain lies with sunflowers (21%-41%), with the least for maize (8%-12%).

Incremental yield

Incremental yield refers to the percentage increase in crop yield for irrigated crops compared to rainfed crops of the same type, specifically considering maize, soybeans, wheat & barely, and sunflower. Depending on the specific scheme, irrigated crops experience an average yield increase ranging from 5% o 80% compared to respective rainfed crops. 16 out of 20 schemes achieve the target level of a 50% increase in yield with respect to rainfed areas in at least one year (out of 2017-2021) for at least one crop. Among all the crops, maize benefits the most from irrigation, with an average yield increase of 60% across all schemes (Supplementary Figure 4C), although it requires more water. The northern schemes tend to have lower values due to the higher yield of rainfed crops in those regions. This can be attributed to lower summer temperatures, which result in lower irrigation requirements. Consequently, the average yield of irrigated crops is not significantly higher than that of rainfed crops.

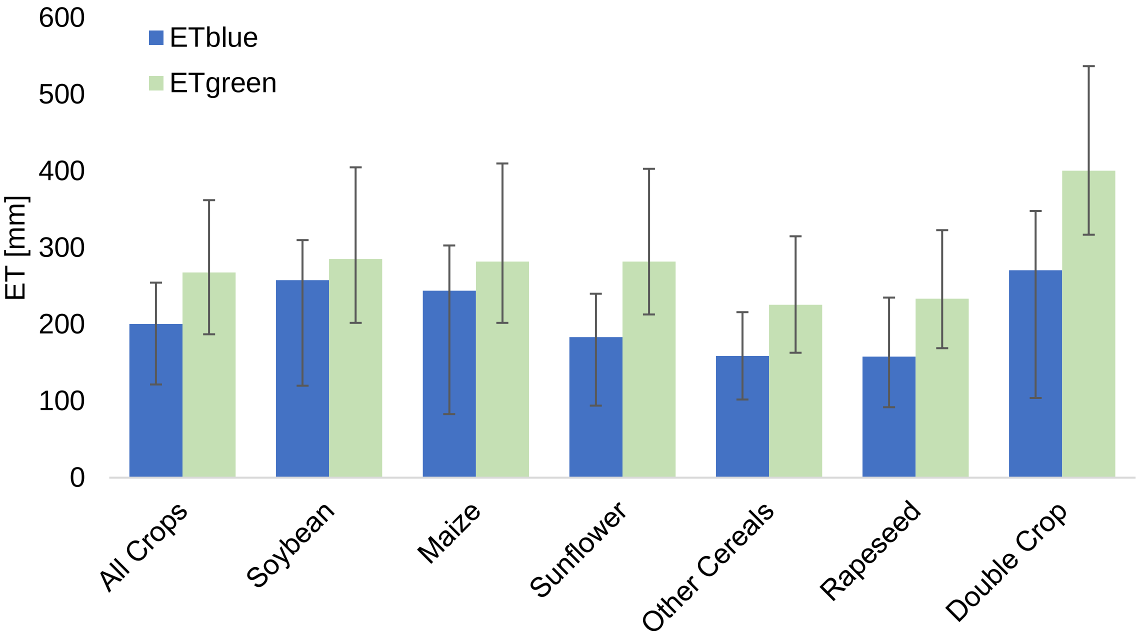
Irrigation efficiency

The system-level irrigation efficiency evaluates both the conveyance and application efficiencies by dividing the irrigation water consumption by the total irrigation supply. It measures the percentage of irrigation water supply that is productively utilized through evapotranspiration. By focusing on evapotranspiration from irrigation, we isolate the water consumption specifically associated with irrigation, excluding rainfall, and assess the efficiency of irrigation water usage. The State Agency for Water Resources (SAWR) provides data on the total withdrawn irrigation water per canal system for the year 2019 for Kakhovka, Chaplynska and Sirogozka irrigation schemes in Kherson. For Kakhovka and Sirogozka schemes, we calculated irrigation efficiencies of 32% and 29%, respectively. The low efficiency of the Kakhovka irrigation scheme in Kherson Oblast can be attributed to significant conveyance losses, as only 46% of the withdrawn water reaches the fields (State Agency for Water Resources, 2023). As the Kakhovka irrigation scheme is a pumped irrigation system, the low conveyance efficiency leads to high energy consumption. The field efficiency, however, is relatively high (60%) because sprinkler irrigation is mainly used. A very low irrigation efficiency of 11% was estimated for Chaplynska scheme. This is a small scheme in Kherson Oblast (command area of about 5000 ha) whose main canal is gravity-fed and where surface irrigation is common. Despite potential uncertainties, the results demonstrate substantial variations in irrigation efficiency between systems. There is a significant potential for water savings, particularly in the Kakhovka irrigation scheme, which happens to be the largest scheme in Ukraine and Europe (Reznik et al., 2016; Shumilova et al., 2023).

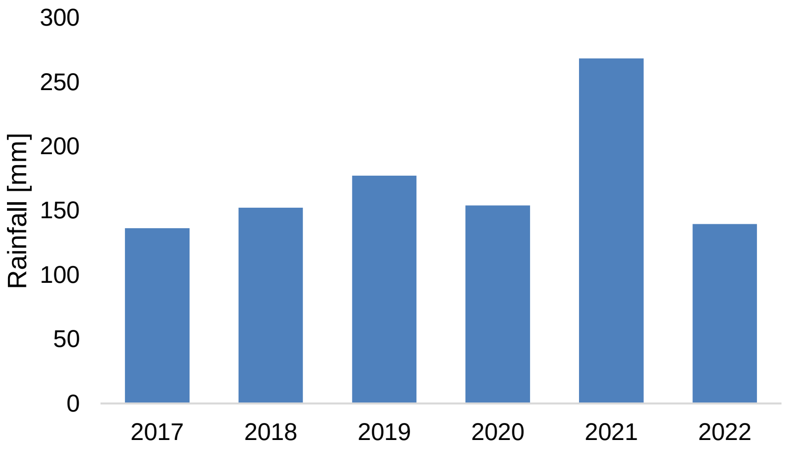
Supplementary Table 1. Ukrainian's irrigation schemes. The most common irrigated crop per scheme has been identified based on the remote sensing analysis.

ID	Irrigation System (s)	Region(s)	Command Area (ha)	Most Common Irrigated Crop
1	Bilgorod-Dnestrovska	Odesa	9969	Sunflower
2	Bortnitska	Kiev	33041	Other crops
3	Chaplynska	Kherson	4863	Maize
4	Magdalinovska	Dnipropetrovsk	16977	Sunflower
5	Dunay-Dnestrovska	Odesa	142192	Rapseed
7	Frunzenska	Dnipropetrovsk	50615	Soybeans

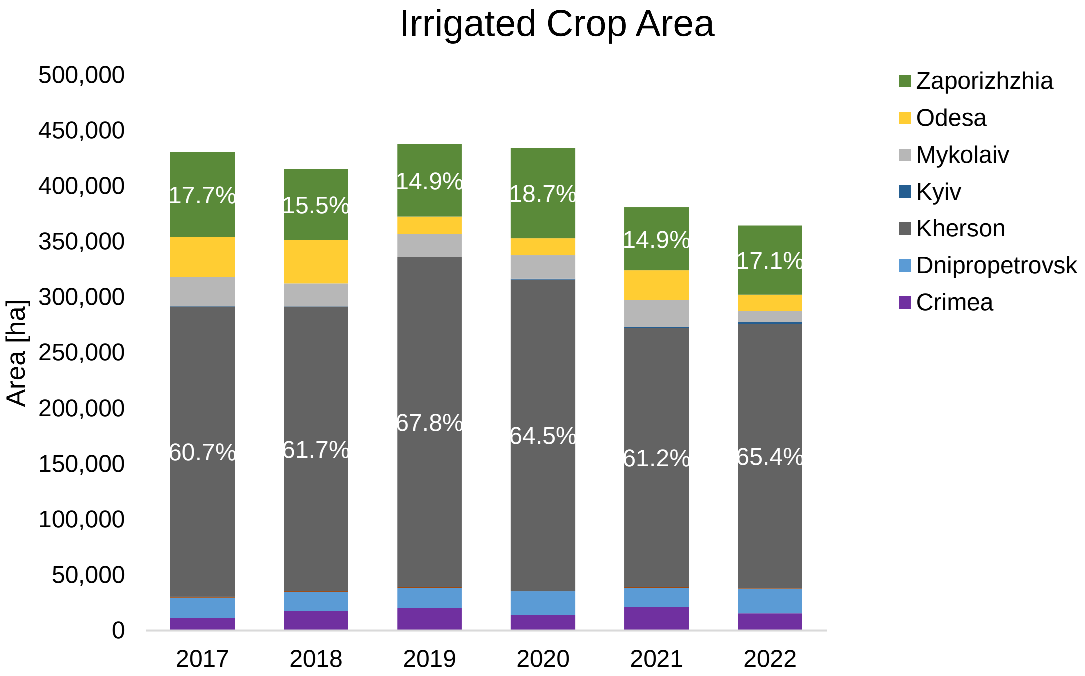
8	Inguletska	Mykolaiv	99824	Soybeans
9	Kakhovka	Kherson	289098	Soybeans
10	Nizhne-Dnestrovska	Odesa	164222	Soybeans
11	North Crimea	Kherson	56237	Maize
12	Oleksandrivska	Kherson	58381	Maize
13	Pivdenno-Bugska	Mykolaiv	14792	Sunflower
14	Pivnichno-Rogachinska	Zaporizhzhia	122501	Cereal crops
15	Priazovska	Zaporizhzhia	47157	Soybeans
16	Sirogozska	Kherson	32540	Soybeans
17	Spaska	Mykolaiv	13528	Soybeans
18	Tatarburnarska	Odesa	58587	Cereal crops
19	Vilnyanska	Zaporizhzhia	6158	Maize
20	Yavkinska	Mykolaiv	32632	Cereal crops
21	Zhovtneva	Zaporizhzhia	19421	Cereal crops



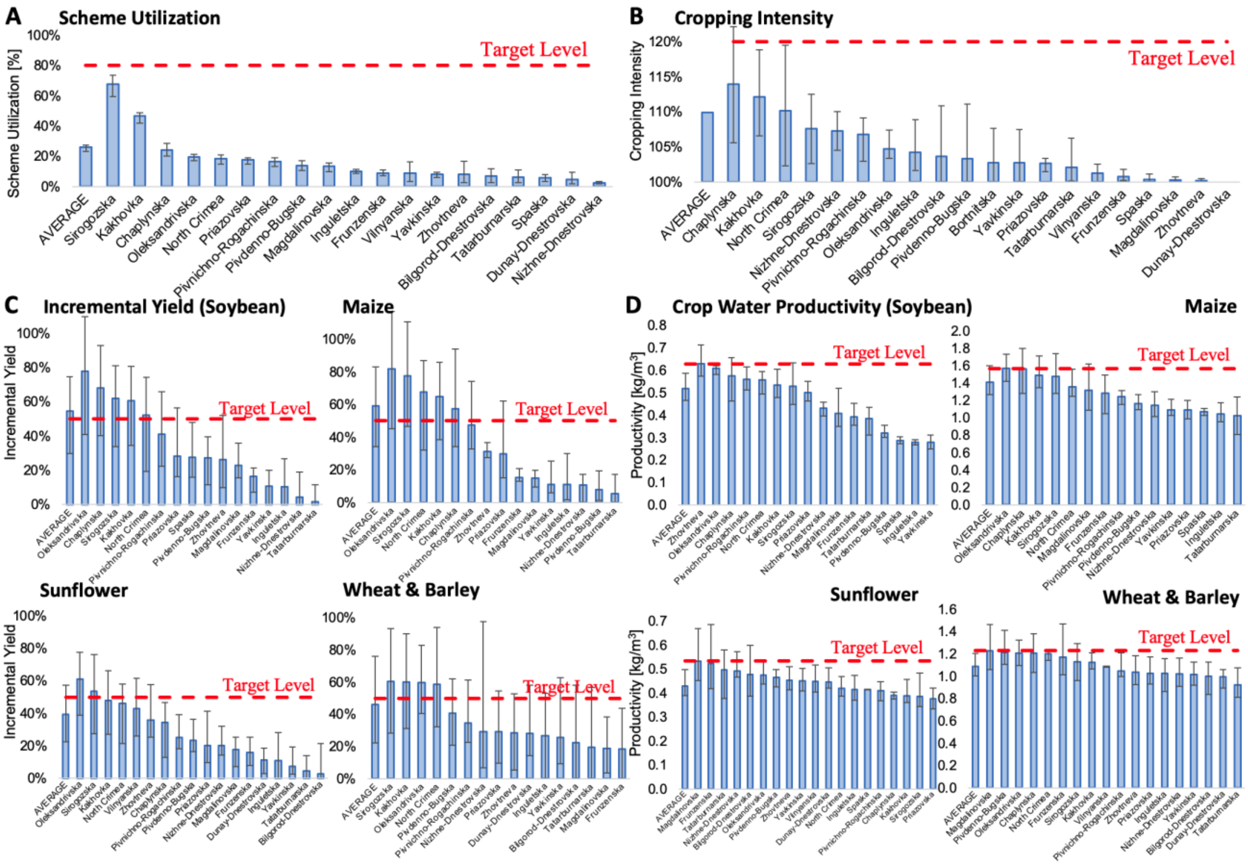
Supplementary Figure 1. Annual average ETblue and ETgreen for the period 2017-2021 over irrigated areas in Ukraine and over irrigated areas of specific crop classes, respectively. ‘Other Cereals' mainly represent wheat and barley. ‘All Crops’ denominate all crops in single crop rotations (without double cropping). Error bars show the full range of annual values of the five main regions in Ukraine where irrigation is commonly practiced (Dnipropetrovsk, Kherson, Mykolaiv, Odesa and Zaporizhzhia).



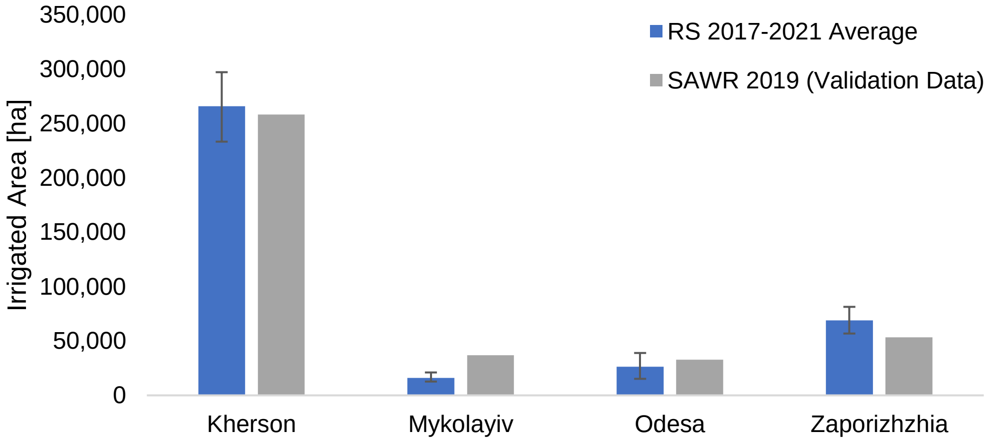
Supplementary Figure 2. Average rainfall during the vegetation periods of irrigated crops.



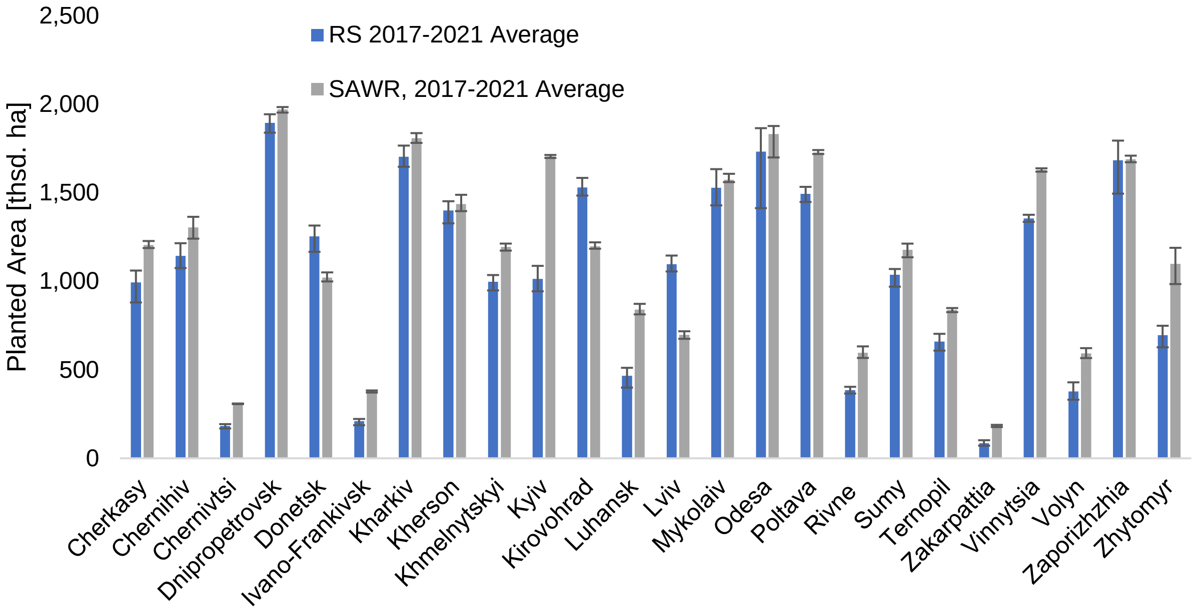
Supplementary Figure 3. Irrigated area by Oblast from the remote sensing analyses.



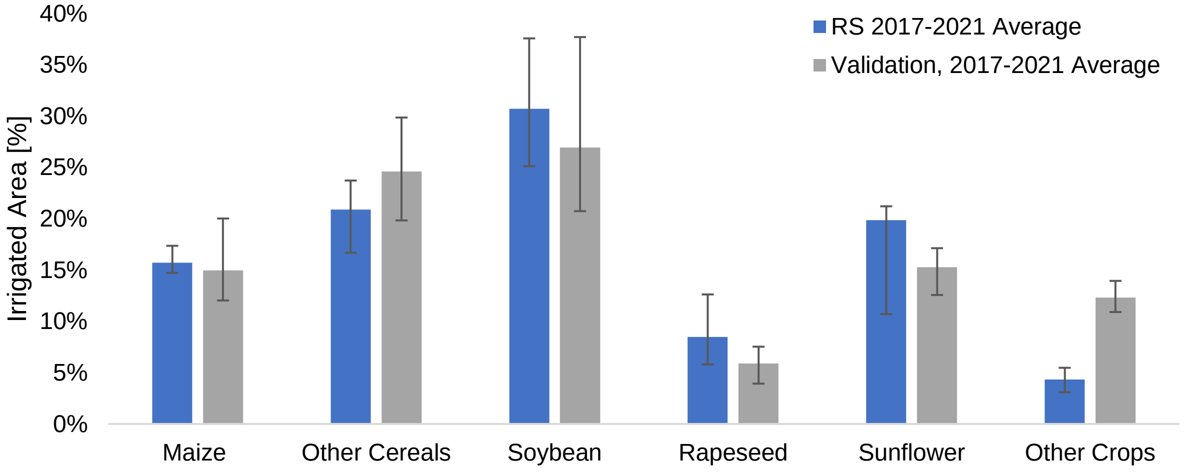
Supplementary Figure 4. Cropping intensity, crop water productivity, incremental yield, and irrigation efficiency of 20 large irrigation schemes in Ukraine in 2017-2021. Error bars indicate the full range of observed values, while the red dotted lines show Target Levels that are defined based on a combination of local and international best practices. 'Average' represents the average value over all irrigated areas within the boundaries of the 20 schemes.



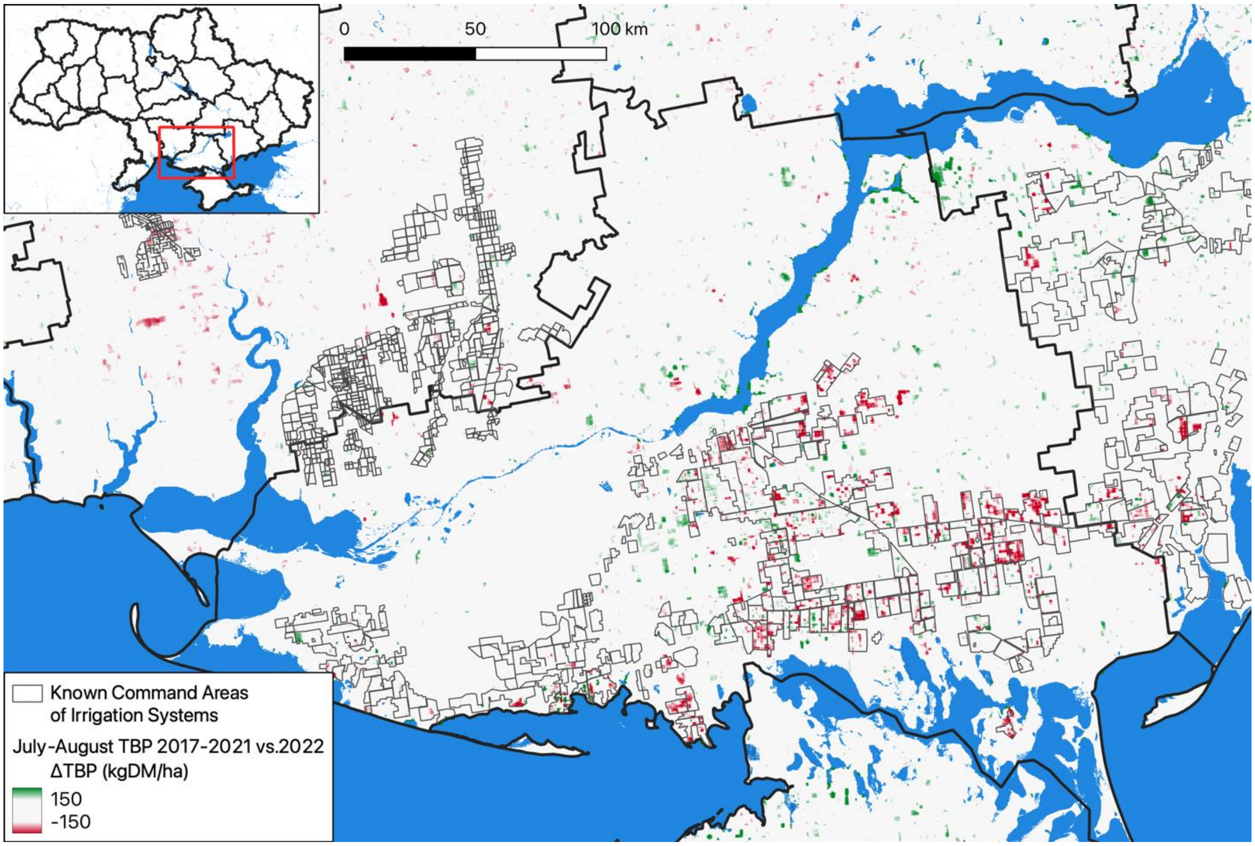
Supplementary Figure 5. Irrigated area per Oblast according to census data and according to the maps generated by remote sensing (RS). Census data are from Ukraine's State Agency for Water Resources. Data for oblasts other than the four specified are unavailable. The error bars represent the full range of values over the period 2017-2021.



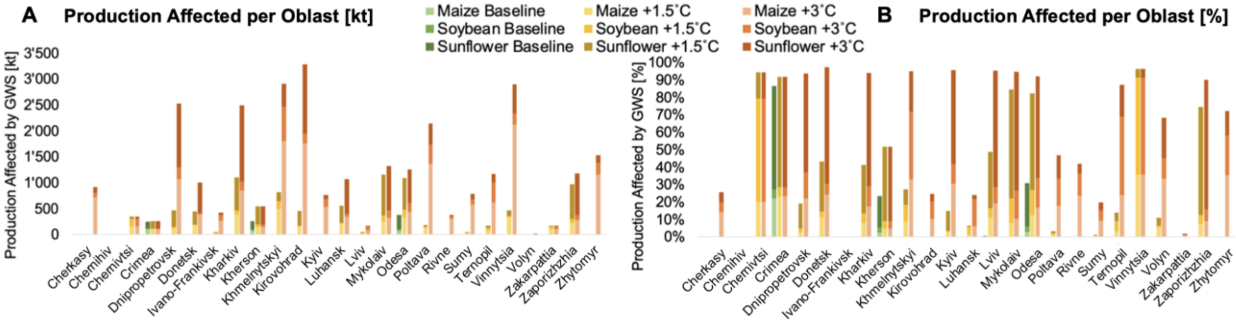
Supplementary Figure 6. Planted area per Oblast according to census data (SAWR) and according to the maps generated by remote sensing (RS). Census data are from Ukraine's State Agency for Water Resources. The error bars represent the full range of values over the period 2017-2021.



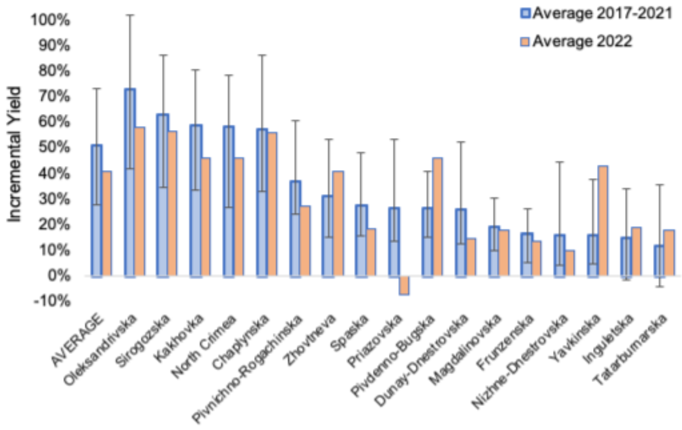
Supplementary Figure 7. Fraction of irrigated area per major crop type according to census data (SAWR) and according to the maps generated by remote sensing (RS). Census data are from Ukraine's State Agency for Water Resources. The State Agency for Water Resources data on irrigated areas does not reflect the irrigated areas of all agricultural holdings, but only of enterprises (data from private farms are not available). The error bars represent the full range of values over the period 2017-2021.



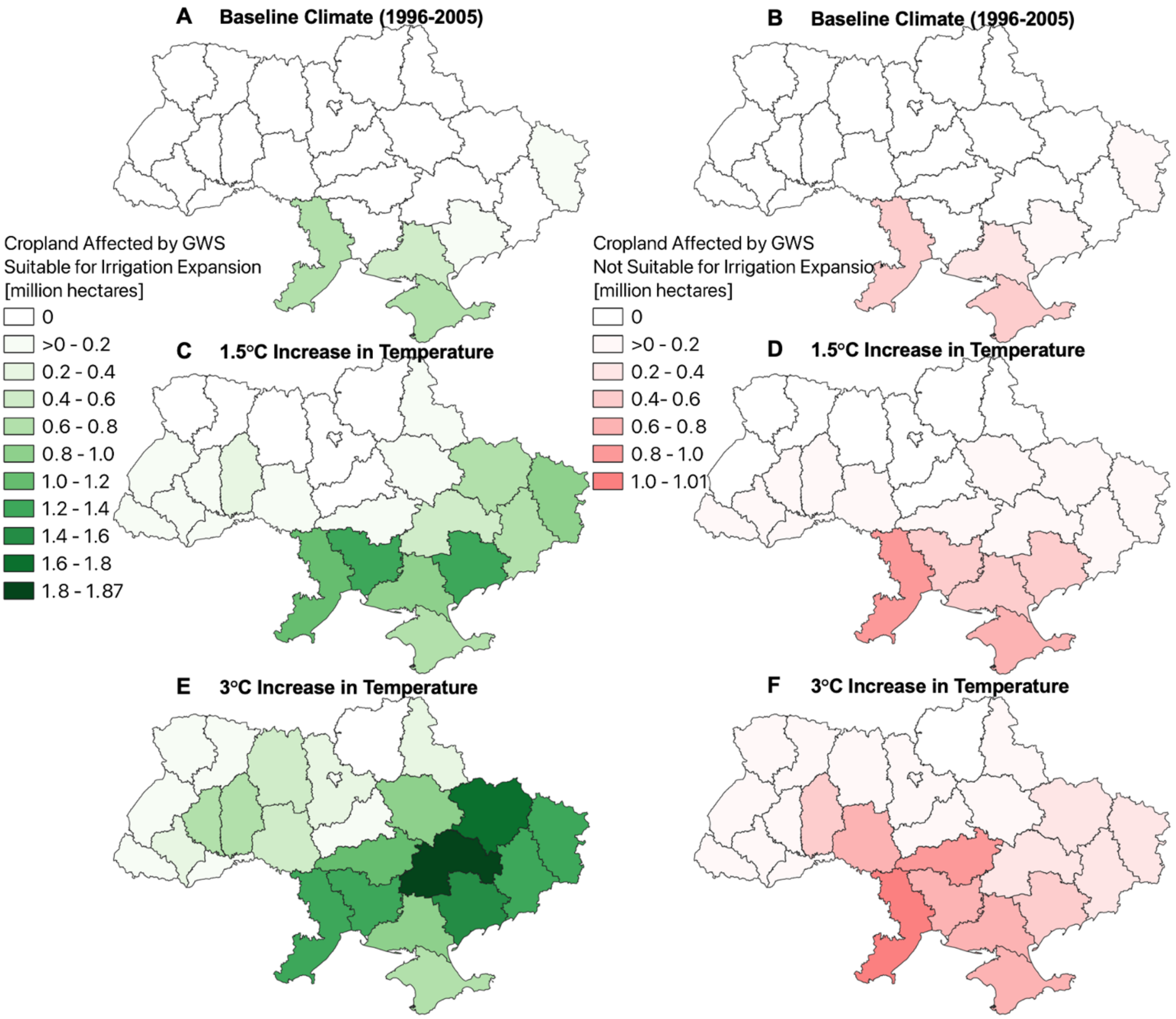
Supplementary Figure 8. Remote sensing data on change in biomass production over irrigated areas. The map shows the difference between July-August average Total Biomass Production (TBP) over the years 2017-2021 and July-August TBP of the year 2022.



Supplementary Figure 9. Crop production affected by Green Water Scarcity (GWS). Results are shown per Oblast and by climate scenario (green shades: baseline climate, yellow shades: +1.5˚C, red shades: +3˚C). Panel A presents the total affected production in thousand tons (kt). Panel B presents the affected production as a fraction of the current total production.



Supplementary Figure 10. Weighted average incremental yield by area fraction and crop type of 20 large irrigation schemes in Ukraine, 2017-2021 and 2022. Interval bars indicate the full range of annual observed values over 2017-2021. ‘Average’ represents the average value over all irrigated areas within the boundaries of the 20 schemes.



Supplementary Figure 11. Potential for irrigation expansion in Ukraine under warming scenarios. Maps A, C and D show the cropland area (in million hectares, per oblast) affected by GWS and suitable for irrigation expansion under baseline climate, 1.5 °C, and 3 °C warmer climate conditions. Maps B, D and F show the cropland area per oblast affected by GWS not suitable for irrigation expansion due to insufficient local water availability for sustainable exploitation.

Supplementary Table 2. Croplands affected by Green Water Scarcity (GWS) and suitability for irrigation expansion. The table shows the areas suitable and unsuitable for sustainable irrigation expansion. Results are listed by Oblast and by climate scenario (cr: baseline climate, 1.5c: +1.5˚C, 3c: +3˚C).

Oblast	**Climate**	**Croplands**	**GWS**	**Sustainable irrigation**	**Unsustainable irrigation**
		[ha]	**[ha]**	**[ha]**	**[ha]**
Cherkasy	cr	1243365	0	0	0

Cherkasy	1.5c	1243365	0	0	0
Cherkasy	3c	1243365	303591	193981	109610
Chernihiv	cr	1479955	0	0	0
Chernihiv	1.5c	1479955	0	0	0
Chernihiv	3c	1479955	0	0	0
Chernivtsi	cr	269210.4	0	0	0
Chernivtsi	1.5c	269210.4	269210	199606	69604
Chernivtsi	3c	269210.4	269210	192725	76485
Crimea	cr	1348691	1160056	661602	498454
Crimea	1.5c	1348691	1348691	715950	632741
Crimea	3c	1348691	1348691	714322	634369
Dnipropetrovsk	cr	2210960	0	0	0
Dnipropetrovsk	1.5c	2210960	587947	475806	112141
Dnipropetrovsk	3c	2210960	2201381	1869893	331488
Donetsk	cr	1796070	0	0	0
Donetsk	1.5c	1796070	829881	693243	136638
Donetsk	3c	1796070	1796070	1397171	398899
Ivano-Frankivsk	cr	315476.5	0	0	0
Ivano-Frankivsk	1.5c	315476.5	41918	40857	1061
Ivano-Frankivsk	3c	315476.5	304392	261712	42680
Kharkiv	cr	1966244	0	0	0
Kharkiv	1.5c	1966244	846495	769387	77108
Kharkiv	3c	1966244	1966244	1623253	342991
Kherson	cr	1535931	819357	489105	330252
Kherson	1.5c	1535931	1535931	957268	578663
Kherson	3c	1535931	1535931	930362	605569
Khmelnytskyi	cr	1280997	0	0	0
Khmelnytskyi	1.5c	1280997	383168	235210	147958
Khmelnytskyi	3c	1280997	1272629	799051	473578
Kirovohrad	cr	1900637	0	0	0
Kirovohrad	1.5c	1900637	320673.3	187059.6285	133613.7
Kirovohrad	3c	1900637	1876387	1048573.571	827813.6
Kyiv	cr	1203605	0	0	0
Kyiv	1.5c	1203605	0	0	0
Kyiv	3c	1203605	323999.1	276885.4424	47113.62
Luhansk	cr	1565142	30291.31	25646.1486	4645.16
Luhansk	1.5c	1565142	1009847	821469.735	188376.9
Luhansk	3c	1565142	1565142	1203124.941	362017.5
Lviv	cr	719825.5	0	0	0
Lviv	1.5c	719825.5	57829.33	57829.33281	0

Lviv	3c	719825.5	201607.2	199870.2492	1736.992
Mykolaiv	cr	1869518	0	0	0
Mykolaiv	1.5c	1869518	1736441	1209750	526691
Mykolaiv	3c	1869518	1869518	1245325	624193
Odesa	cr	2215900	1114783	651138	463645
Odesa	1.5c	2215900	2115037	1197051	917986
Odesa	3c	2215900	2215900	1202460	1013440
Poltava	cr	1880694	0	0	0
Poltava	1.5c	1880694	69162	61512	7650
Poltava	3c	1880694	971386	849665	121721
Rivne	cr	638975.5	0	0	0
Rivne	1.5c	638975.5	0	0	0
Rivne	3c	638975.5	225773	188544	37229
Sumy	cr	1289748	0	0	0
Sumy	1.5c	1289748	10622	10688	-66
Sumy	3c	1289748	279909	225348	54561
Ternopil	cr	863152.3	0	0	0
Ternopil	1.5c	863152.3	107877	91558	16319
Ternopil	3c	863152.3	779493	613854	165639
Vinnytsia	cr	1730724	0	0	0
Vinnytsia	1.5c	1730724	239585	130642.4091	108942.6
Vinnytsia	3c	1730724	1290478	576125.5999	714352.7
Volyn	cr	503924.9	0	0	0
Volyn	1.5c	503924.9	0	0	0
Volyn	3c	503924.9	10718.76	10144.18662	574.5704
Zakarpattia	cr	158188.7	0	0	0
Zakarpattia	1.5c	158188.7	157764.4	157152.2298	612.2157
Zakarpattia	3c	158188.7	158188.7	156877.0719	1311.672
Zaporizhzhia	cr	2066546	12082.58	7962.15992	4120.415
Zaporizhzhia	1.5c	2066546	1811604	1335607.391	475996.3
Zaporizhzhia	3c	2066546	2066546	1503685.95	562860.2
Zhytomyr	cr	980132.4	0	0	0
Zhytomyr	1.5c	980132.4	0	0	0
Zhytomyr	3c	980132.4	660879	544048	116831

Supplementary Table 3. Crop production affected by Green Water Scarcity (GWS). Results are listed by Oblast and by climate scenario (cr: baseline climate, 1.5c: +1.5˚C, 3c: +3˚C).

Name	Climate	Maize [kt]	Maize [%]	Soybean [kt]	Soybean [%]	Sunflower [kt]	Sunflower [%]
Cherkasy	cr	0	0.0%	0	0.0%	0	0.0%
Cherkasy	1.5c	0	0.0%	0	0.0%	0	0.0%
Cherkasy	3c	1055	26.2%	399	26.9%	430	23.4%
Chernihiv	cr	0	0.0%	0	0.0%	0	0.0%
Chernihiv	1.5c	0	0.0%	0	0.0%	0	0.0%
Chernihiv	3c	0	0.0%	0	0.0%	0	0.0%
Chernivtsi	cr	0	0.0%	0	0.0%	0	0.0%
Chernivtsi	1.5c	223	95.7%	661	93.6%	167	95.9%
Chernivtsi	3c	223	95.7%	661	93.6%	167	95.9%
Crimea	cr	177	84.4%	40	67.5%	472	89.6%
Crimea	1.5c	185	88.5%	43	71.5%	504	95.6%
Crimea	3c	185	88.5%	43	71.5%	504	95.6%
Dnipropetrovsk	cr	0	0.0%	0	0.0%	0	0.0%
Dnipropetrovsk	1.5c	229	10.3%	214	14.1%	1329	24.3%
Dnipropetrovsk	3c	2034	91.9%	1379	91.1%	5219	95.4%
Donetsk	cr	0	0.0%	0	0.0%	0	0.0%
Donetsk	1.5c	484	45.7%	133	47.1%	1221	42.1%
Donetsk	3c	1029	97.1%	272	96.3%	2832	97.7%
Ivano-Frankivsk	cr	0	0.0%	0	0.0%	0	0.0%
Ivano-Frankivsk	1.5c	30	8.0%	63	12.3%	28	14.2%
Ivano-Frankivsk	3c	347	91.3%	456	89.5%	182	92.7%
Kharkiv	cr	0	0.0%	0	0.0%	0	0.0%
Kharkiv	1.5c	708	42.9%	503	45.0%	2454	40.4%
Kharkiv	3c	1556	94.3%	1027	92.0%	5735	94.3%
Kherson	cr	96	15.9%	120	10.5%	692	32.2%
Kherson	1.5c	186	30.9%	173	15.1%	1661	77.4%
Kherson	3c	186	30.9%	173	15.1%	1661	77.4%
Khmelnytskyi	cr	0	0.0%	0	0.0%	0	0.0%
Khmelnytskyi	1.5c	601	25.7%	640	23.2%	604	36.9%
Khmelnytskyi	3c	2228	95.3%	2625	95.0%	1553	95.0%
Kirovohrad	cr	0	0.0%	0	0.0%	0	0.0%
Kirovohrad	1.5c	0	0.0%	0	0.0%	0	0.0%
Kirovohrad	3c	755	22.3%	726	29.5%	294	21.4%
Kyiv	cr	0	0.0%	0	0.0%	0	0.0%
Kyiv	1.5c	284	8.8%	86	7.0%	1125	20.2%
Kyiv	3c	3076	95.5%	1142	93.5%	5375	96.4%
Luhansk	cr	0	0.0%	0	0.0%	0	0.0%
Luhansk	1.5c	21	3.8%	86	7.8%	14	7.8%
Luhansk	3c	114	20.4%	289	26.3%	37	20.6%
Lviv	cr	7	0.7%	2	0.5%	11	0.3%
Lviv	1.5c	510	54.7%	267	57.3%	1487	45.8%
Lviv	3c	885	94.8%	438	94.1%	3107	95.8%
Mykolaiv	cr	0	0.0%	0	0.0%	0	0.0%
Mykolaiv	1.5c	458	73.1%	781	79.6%	3506	87.8%
Mykolaiv	3c	584	93.1%	910	92.7%	3817	95.6%
Odesa	cr	146	15.7%	169	17.4%	1239	39.8%
Odesa	1.5c	640	69.1%	705	72.9%	2780	89.4%
Odesa	3c	843	91.1%	846	87.5%	2927	94.1%
Poltava	cr	0	0.0%	0	0.0%	0	0.0%
Poltava	1.5c	205	5.0%	75	1.5%	121	4.6%
Poltava	3c	2121	51.3%	1879	36.6%	1561	59.4%
Rivne	cr	0	0.0%	0	0.0%	0	0.0%
Rivne	1.5c	0	0.0%	0	0.0%	0	0.0%
Rivne	3c	411	40.1%	219	41.9%	93	52.2%
Sumy	cr	0	0.0%	0	0.0%	0	0.0%
Sumy	1.5c	52	1.1%	15	0.7%	16	1.1%
Sumy	3c	795	16.8%	500	22.6%	368	24.7%
Ternopil	cr	0	0.0%	0	0.0%	0	0.0%
Ternopil	1.5c	99	11.4%	196	11.5%	155	23.7%
Ternopil	3c	776	88.9%	1457	85.4%	584	89.5%
Vinnytsia	cr	0	0.0%	0	0.0%	0	0.0%
Vinnytsia	1.5c	148	96.9%	230	95.9%	20	95.8%
Vinnytsia	3c	148	96.9%	230	95.9%	20	95.8%
Volyn	cr	0	0.0%	0	0.0%	0	0.0%
Volyn	1.5c	457	10.7%	108	7.0%	362	13.4%
Volyn	3c	2842	66.7%	1015	65.7%	1956	72.4%
Zakarpattia	cr	0	0.0%	0	0.0%	0	0.0%
Zakarpattia	1.5c	0	0.0%	0	0.0%	0	0.0%
Zakarpattia	3c	9	1.7%	7	2.0%	3	1.5%
Zaporizhzhia	cr	1	0.1%	1	0.2%	8	0.2%
Zaporizhzhia	1.5c	381	65.2%	266	52.5%	3138	78.7%
Zaporizhzhia	3c	461	78.9%	347	68.5%	3776	94.7%
Zhytomyr	cr	0	0.0%	0	0.0%	0	0.0%
Zhytomyr	1.5c	0	0.0%	0	0.0%	0	0.0%
Zhytomyr	3c	1587	73.1%	1013	74.2%	615	66.7%