

The revival of irrigation in the Southern Steppe is a guarantee of Ukraine's food security

Valentyna Gamajunova

Doctor of Agricultural Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-4151-0299>

Iryna Smirnova*

PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-8976-3818>

Lyubov Khonenko

PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-5365-8768>

Tetiana Baklanova

PhD in Agricultural Sciences Associate Professor
Mykolayiv State Agricultural Research Station of the Institute of Climate-Smart Agriculture of the
National Academy of Agrarian Sciences of Ukraine
57217, 17 Tsentralna Str., Polihon, Ukraine
<https://orcid.org/0000-0002-6699-2693>

Abstract. The aim of the study was to determine the effects of irrigation regimes and mineral nutrition systems on crop productivity, nitrogen balance and soil fertility indicators under the conditions of the Southern Steppe of Ukraine. The article presented the results of long-term stationary field experiments conducted at the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine over periods ranging from 5 to 40 years, depending on the crop, on dark chestnut soils, as well as experiments conducted at the Educational, Science and Research Center of Mykolaiv National Agrarian University during 2021-2025 on southern chernozem. Conventional field experiment methods, laboratory and analytical measurements, and analysis of variance were employed. Irrigation was found to be the main factor in stabilising crop yields in the arid region: depending on the crop, yields were, on average, two to three times higher than under rainfed conditions and, in extremely dry years, five or more times higher. The highest irrigation indices were recorded for grain maize (3.4), alfalfa (3.3) and silage maize (3.2). For winter wheat, the combination of a biologically optimal irrigation regime with the recommended $N_{60}P_{30}K_{30}$ fertiliser rate increased yield by 70.4% compared with the unfertilised control, whereas the water-saving irrigation regime also ensured stable yields of 7.0-7.4 t/ha. It was demonstrated that irrigation substantially increased nutrient removal, particularly nitrogen removal, resulting in a negative soil nitrogen balance if these

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*Corresponding author (smirnovaiv@mnaeu.edu.ua)



losses were not compensated for. The stabilisation and increase of soil humus stocks by 150-200 kg/ha annually were achieved only through an integrated organic-mineral fertilisation system involving manure and optimal rates of mineral fertilisers within the crop rotation. The results obtained confirm the benefits of combining irrigation with balanced fertilisation to increase crop productivity, improve water-use efficiency, and preserve soil fertility, thereby providing a scientific basis for modernising irrigation systems in the Southern Steppe of Ukraine under changing climatic conditions.

Keywords: climate change; irrigation regime; fertilisation system; nitrogen balance; soil fertility; winter wheat

INTRODUCTION

The Southern Steppe of Ukraine is characterised by unstable moisture conditions and high risks in agricultural production, and prolonged periods of moisture deficit during the growing season lead to year-to-year variability in yields and often result in low yields without supplemental irrigation. According to the World Bank (Sinha *et al.*, 2024), prior to the start of Russia's full-scale invasion, approximately 1.6% of Ukraine's agricultural land was irrigated, with irrigation infrastructure concentrated primarily in the southern regions. Irrigation in this region is of critical importance for sustainable agricultural production and the country's food security. According to R. Sinha *et al.* (2024), the restoration of Ukraine's irrigation infrastructure requires significant investment, the modernisation of water management systems, and coordinated policy decisions. The authors of the report emphasise the need to adapt irrigation technologies to climate change, improve the efficiency of water use, and attract investment to ensure sustainable agricultural production amid increasing water shortages.

According to V. Pichura & L. Potravka (2025), in the southern regions of Ukraine (Kherson, Mykolaiv, Odesa, and parts of Zaporizhzhia Oblasts), irrigation has historically ensured a significant increase in the productivity of all agricultural crops, with the Kakhovka Reservoir cascade (Middle Dnipro Complex) serving as the main source of irrigation water in this area. The destruction of the dam and a significant reduction in water flow in 2023 greatly complicated the situation, disrupting irrigation regimes across large areas, which created an urgent need to restore infrastructure and adapt technologies. V. Pichura & L. Potravka (2025) found that the collapse of the Kakhovka Reservoir in 2023 caused significant changes in the agroecosystems of the Southern Steppe of Ukraine, including a reduction in irrigated land area, an increase in soil surface temperature, a rise in moisture deficit, and heightened risks of erosion processes. These findings highlight the need to consider the environmental consequences of disruptions to irrigation systems when planning their restoration and modernisation.

G. Hapich & D. Onopriienko (2024) found that the destruction of the Kakhovka Reservoir had significant environmental and economic consequences for agricultural production in southern Ukraine, including a sharp reduction in irrigated areas and increased risks to the region's food security. The authors emphasise the need for systematic restoration and modernisation of the irrigation infrastructure. According to N. Markova *et al.* (2025), the use of irrigation in the Southern Steppe region of Ukraine resulted in a 28-48% increase in sunflower yields, a 15-25% increase in winter wheat yields, and a 25-35% increase in rapeseed yields. In studies conducted in 2022-2024 in the Southern Steppe of Ukraine, N. Markova *et al.* (2025) compared three irrigation regimes: no irrigation, optimal, and excessive. The authors determined their impact on crop yield, agricultural product quality, and the economic efficiency of crop production. The results obtained made it possible to assess the feasibility of applying different irrigation regimes under arid climatic conditions. P. Lykhovyd (2021) determined that 46.1% of Ukraine's arable land cannot support sustainable agricultural production without irrigation, while 42.7% of the area requires irrigation for growing crops with high water demands. The author noted that under arid conditions, water supply to plants is one of the main limiting factors affecting their productivity.

The effectiveness of irrigation technologies is significantly enhanced through the implementation of adaptive water resource management systems and the use of modernised irrigation methods. According to research by V. Kaliley *et al.* (2023), it has been established that the design of drip irrigation systems, specifically, the method of laying pipes in a horizontal or vertical plane and the pulsed water delivery mode – is crucial for achieving optimal irrigation conditions, yield, and water efficiency when growing sunflower hybrids. Researchers V. Kaliley & A. Shatkovskyi (2022) determined that laying pipes 0.3 m deep in the subsoil with a spacing of 1.0 m between them resulted in a seed yield of 4.01-4.09 t/ha, a water consumption coefficient of 1,088.7-1,125.7 m³/t, and an irrigation water use efficiency of

2.27-2.41 kg/m³. The results confirm the importance of optimising the design parameters of irrigation systems to improve the efficiency of crop cultivation.

With regard to water application technologies, modern systems, such as drip and micro-irrigation, sprinkler systems, and fertigation, allow for a significant increase in water use efficiency (WUE). However, in their publications, Ukrainian scientists emphasise that, in addition to using these technologies, it is essential to properly design drainage systems, monitor soil salinisation, and apply organic fertilisers. Research conducted in the Southern Steppe region of Ukraine by V. Gamajunova *et al.* (2025) found that prolonged irrigation can improve the soil's physical and hydraulic properties by lowering temperature and enhancing water-holding capacity, but at the same time, it can lead to soil compaction and increased leaching of nutrients, which requires the additional application of organic matter. O. Bazaluk *et al.* (2022) investigated the potential for applying "smart" irrigation systems based on Low-Cost Smart Farm Irrigation Systems technology. Based on the results of five years of field studies, the authors concluded that the use of such a system makes it possible to reduce water consumption and increase the efficiency of water resource use. Researchers Iu. Lavrynenko *et al.* (2020) investigated the adaptive capacity of Ukrainian-bred corn hybrids to various irrigation regimes under the arid conditions of the Ukrainian Steppe. The authors found that the productivity of the hybrids depended significantly on the method of moisture supply to the plants, specifically under conventional sprinkler irrigation, drip irrigation, and sub-irrigation.

A review of the literature indicates that the implementation of well-founded and modern approaches to irrigation in the Southern Steppe of Ukraine can significantly increase crop yields, improve water use efficiency, and ensure economic returns, provided that crops are simultaneously adapted to climate change. However, to maximise effectiveness, it is necessary to take into account local agroclimatic conditions, ensure proper design and irrigation regimes, and invest in modern irrigation technologies and monitoring systems. The aim of the study was to comprehensively assess the impact of various irrigation regimes and nutrient optimisation on crop productivity, changes in the nitrogen balance, and shifts in soil fertility indicators in the Southern Steppe of Ukraine under current climatic challenges.

MATERIALS AND METHODS

Field studies were conducted in the Southern Steppe region of Ukraine at the experimental fields of the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine (IIA NAAS) as part of

long-term stationary experiments on dark chestnut soil, and at the Science and Research Center of Mykolaiv National Agrarian University (ESPC of MNAU) from 2021 to 2025 on southern chernozem. The experiments were conducted within the Inhulets Irrigation System. The soil of the experimental plot was characterised by a moderate humus content (2.2-2.8%), a neutral or slightly alkaline soil solution reaction (pH 6.8-7.5), moderate to high availability of mobile forms of phosphorus and potassium, and insufficient nitrogen. The region's climate is arid, with frequent summer droughts, uneven precipitation distribution throughout the year, and a high frequency of dry winds. The treatment combinations in the winter wheat experiment were arranged using the split-plot design with four replications. The area of each plot ranged from 50 to 100 m². The experimental design included the following treatments: Factor A – irrigation regime: biologically optimal (pre-irrigation moisture threshold of 70% of the soil's minimum water-holding capacity (WHC) in the 0-50 cm layer), water-conserving (2 irrigations of 450 m³/ha during critical growth stages), soil-conserving (pre-irrigation moisture threshold of 70% of H in the 0-30 cm layer); Factor B – nutrient optimisation: no fertilisers (control), recommended dose of N₆₀P₃₀K₃₀, N₃₀ + foliar applications of biological preparations during the spring tillering and heading stages. Winter wheat was grown following a pea crop; Factor C – winter wheat cultivar: Vidrada, Perlyna Stepu.

In long-term field experiments, elevated doses of mineral fertilisers (NPK2) and an organic-mineral fertilisation system were also used, involving the application of 80 metric tons per hectare of semi-decomposed manure once per rotation of a 7-field crop rotation (three-year alfalfa – winter wheat – grain corn – silage corn – winter wheat). Soil tillage was carried out in accordance with zonal recommendations for the soil and climatic conditions of the Ukrainian Steppe (Order of the Ministry of Agrarian Policy of Ukraine and the Ukrainian Academy of Agrarian Sciences No. 440/71, 2008). In some of the experiments conducted at the Science and Research Center of Mykolaiv National Agrarian University, the Mzuri Pro-Till technology (Poland) was used, involving localised loosening and in-row fertiliser application. Irrigation was carried out by sprinkler or drip irrigation (for vegetable crops). Irrigation rates were determined based on soil moisture measurements using the thermostatic-gravimetric method, maintaining a specified pre-irrigation moisture level (as a percentage of field capacity). Phenological observations were conducted throughout the growing season using standard methods to determine the onset of major plant development

stages, the duration of inter-stage periods, and plant density. Soil moisture was determined using the thermostatic-gravimetric method in the 0-30 and 0-50 cm layers before and after irrigation, by drying the samples at 105°C to constant weight and converting the results to % relative to field capacity. Humus content was determined using the Tyurin method, while mobile forms of nitrogen, phosphorus, and potassium were determined using current standard methods of agrochemical analysis, with soil nutrient status assessed according to an established scale. Yields were recorded by harvesting the entire plot and converting the results to 100% purity and standard grain moisture content. The nitrogen balance was calculated as the difference between inputs (fertilisers, precipitation, irrigation water, and biological fixation) and outputs via harvests, taking into account the actual productivity of the crops in the crop rotation.

The effectiveness of irrigation and fertilisation was assessed based on the irrigation index, absolute and relative yield increases, the return on investment for 1 kg of NPK in terms of additional production, productivity in feed units, changes in humus reserves, and the proportion of land actually irrigated. The irrigation index was defined as the ratio of yield under irrigation to yield without irrigation; yield increase was defined as the difference and as a percentage relative to the control. The return on NPK was defined as the amount of additional production per 1 kg of active fertiliser ingredient. Changes in humus reserves were calculated for the 0-30 cm layer in kg/ha per year, and the proportion of land actually irrigated was calculated as a percentage of the total area of irrigated land. Irrigation water efficiency was determined by the yield increase per 1 m³ of water used, in kg/m³. To analyse trends in irrigated land, statistical data for 1990, 2012, and 2024-2025 were used for the Dnipropetrovsk, Zaporizhzhia, Mykolaiv, Odesa, and Kherson oblasts. Data for 1990 and 2012 were taken from materials of the State Agency of Water Resources of Ukraine, as summarised by R.A. Vozhehova *et al.* (2013); data for 2024-2025 were taken from statistical data compiled by the authors from water management organisations (State Agency of Ukraine for the Development..., 2024; 2025). For 1990 and 2012, the proportion of irrigated land in the total arable land area was determined; for 2024, the proportion of actually irrigated land in the total irrigated land area was determined. Relative indicators were calculated as the ratio of the corresponding area to the base area, multiplied by 100%. To assess trends, the absolute and relative changes in irrigated areas were determined. The experimental data were analysed using a three-factor analysis

of variance (ANOVA) to determine the effects of the factors and their interactions. Statistical significance was assessed at the $p < 0.05$ level. The reliability of differences between mean values was determined using the least significant difference (LSD05) criterion. Statistical calculations were performed using AgroStat software, taking into account the specific features of the field experiment design.

RESULTS

The Southern Steppe of Ukraine is characterised by significant potential for irrigated agriculture; however, the reduction in the area of irrigated land and the underutilisation of existing irrigation systems significantly limit the possibilities for stable agricultural production. The Southern Steppe of Ukraine is characterised by significant potential for irrigated agriculture; however, the reduction in the area of irrigated land and the underutilisation of existing irrigation systems significantly limit the possibilities for stable agricultural production. Given the increasingly arid climate, water scarcity, and the growing frequency of adverse hydrometeorological phenomena, the efficient use of irrigated land is of particular importance for ensuring the productivity of agricultural production in the Southern Steppe of Ukraine. One of the key factors in improving the efficiency of agriculture in the region is the rational use of water resources and the improvement of irrigation technologies. Given the ongoing climate changes that are affecting crop productivity and the reduction in available water resources, irrigation in Ukraine is at significant risk. The Southern Steppe region of Ukraine is particularly vulnerable, as it is gradually transforming from a steppe zone into a semi-desert. Irrigated lands in this region have been and must continue to be key factors in ensuring Ukraine's food security. After all, of the three main natural and climatic zones, the Steppe (40%) is classified as arid, the Forest-Steppe (35% of the total agricultural land area) is considered under-moistened, and Polissya (25%) is considered a moist zone. For this reason, even at the outset of the large-scale implementation and use of land reclamation, the largest areas of irrigated land were concentrated precisely in the southern regions of Ukraine (Table 1). The area of irrigated land in Ukraine peaked in 1990 at 2,287.1 thousand hectares, accounting for 7.0% of the total arable land area. Naturally, the lion's share of this land was concentrated in the southern region. By 2012, the area under irrigation had already decreased significantly. Specifically, in Ukraine, it had fallen to 604.2 thousand hectares, or 1.8% of arable land. The same trend was observed in the southern regions, as shown in Table 1. However, in this region,

the area under irrigation remained significant compared to other regions. For example, in the Kherson region alone, 287.4 thousand hectares, or 16.2% of the total arable land, were irrigated in 2012. Overall, the

southern region accounted for 420.0 thousand hectares out of Ukraine's 604.2 thousand hectares of irrigated land, representing nearly 70% of the total area of irrigated land.

Table 1. Areas of irrigated land in the Steppe region of Ukraine

Oblasts	1990		2012	
	thousand hectares	as a % of total arable land	thousand hectares	as a % of total arable land
Dnipropetrovsk	219.6	10.4	27.1	1.3
Zaporizhzhia	269.0	14.2	43.8	2.3
Mykolaiv	184.1	10.8	21.2	1.2
Odesa	218.6	10.5	40.5	1.9
Kherson	444.6	25.1	287.4	16.2
Total for the listed regions of Ukraine	1,335.9	4.1	420.0	1.3

Source: based on data from the State Agency of Water Resources of Ukraine (n.d.) and R.A. Vozhehova et al. (2013)

According to R.A. Vozhehova et al. (2013), the area of irrigated land in these regions was 1,335.9 thousand hectares in 1990 and 420.0 thousand hectares in 2012. This once again underscores the importance and necessity of irrigation in the steppe region, where, especially during severe drought years, it is practically impossible to achieve stable crop yields without irrigation. In light of this and climate change, the Cabinet of Ministers of Ukraine approved the "Strategy for Irrigation and Drainage in Ukraine for the period up to 2030" in 2019 (Order of the Cabinet of Ministers of Ukraine No. 688-r, 2019), which called for increasing the area of irrigated land to 1.5-1.8 million hectares, draining excess water in the spring across more than 3 million hectares, and regulating water during the growing season across an area of more than 1 million hectares. The objectives of this

project were to create the conditions for Ukraine to become a competitive producer of agricultural products on the global market. Studies conducted by the Institute of Agricultural Sciences of the National Academy of Agrarian Sciences (NAAS) in the area covered by the Inhulets Irrigation System over a period of 5 to 40 years, depending on the crop, have demonstrated a significant increase in the yields of major agricultural crops under irrigated conditions compared to non-irrigated cultivation. It has been established that irrigation, compared to non-irrigated cultivation, provides significant increases in the yield of all agricultural crops. According to research, which lasted 5-40 years depending on the crop, sufficiently high irrigation indices were determined regardless of the crop: yield levels increase by a factor of 2-3 or more (Table 2).

Table 2. Irrigation efficiency based on data from studies conducted by the Institute of Agricultural Sciences of the National Academy of Agrarian Sciences of Ukraine (NAAS) between 1971 and 2011 (Inhulets irrigation system area)

Crop	Number of years of research	Average irrigation rate, m ³ /ha	Yield, t/ha		Yield increase from irrigation		Irrigation index
			without irrigation	with irrigation	t/ha	%	
Winter wheat	32	2,100	2.99	6.04	3.05	102	2.0
Grain corn	40	2,210	2.86	9.57	6.71	235	3.4
Silage corn	36	2,300	20.3	65.0	44.7	220	3.2
Soybeans	31	2,450	1.07	2.94	1.87	175	2.8
Alfalfa for green forage	19	4,490	19.3	64.1	44.8	232	3.3
Tomatoes	5	3,900	20.3	57.3	37	182	2.8

Note: IIA NAAS – Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine

Source: based on data from IIA NAAS studies conducted between 1971 and 2011 with the participation of some of the authors

The data showed that irrigation significantly increases the yield of all crops: the greatest increase was observed in grain corn (6.71 metric tons per hectare, or 235 %) and silage corn (44.7 metric tons per hectare, or

220 %), as well as alfalfa for green forage (44.8 metric tons per hectare, or 232 %). Winter wheat and tomatoes demonstrate a more moderate, yet still significant, increase in yield from irrigation. The irrigation index

indicates the efficiency of water supply to plants and ranges from 2.0 to 3.4, confirming the positive impact of irrigation on crop productivity under the region's arid conditions. In addition to irrigation, significant yield increases are, of course, achieved by applying the recommended rates of organic and mineral fertilisers to crops in the crop rotation, which is associated with the development of high plant productivity on irrigated lands and, accordingly, a significantly higher uptake of

major nutrients (Table 3). The results of studies conducted by the Institute of Plant Protection of the National Academy of Agrarian Sciences, carried out over a period of 3 to 30 years depending on the crop, demonstrate a significant increase in crop productivity under irrigation conditions when combined with fertiliser application. For example, on average over four rotations of a seven-field crop rotation including alfalfa, the annual increase in forage units was 50.2%.

Table 3. The effect of fertilisers and irrigation on crop yields

Crop	Number of years of research	Yield, t/ha		Yield increase from fertilisers		Payback of 1 kg of NPK in terms of additional yield, kg
		without fertilisers	with the optimal dose of NPK	t/ha	%	
Crops in a 7-field crop rotation (over 4 rotations), fodder units/year	30	5.56	8.35	2.79	50.2	-
Winter wheat (after alfalfa)	5	3.31	5.48	2.17	65.6	14.5
Winter wheat (after corn)	4	2.20	5.45	3.25	147.7	13.5
Corn (grain)	4	4.68	8.53	3.85	82.3	16.2
Spring wheat	3	2.44	3.79	1.35	55.3	7.5
Winter rye	3	2.11	3.83	1.72	81.5	11.5
Soybeans	3	1.78	2.22	0.44	24.7	4.3
Sorgo	3	4.05	6.86	2.81	69.4	13.0
Alfalfa (3-year rotation, hay)	12	24.6	32.3	7.7	31.3	51.0
MVS corn (dry weight)	4	34.7	55.7	21.0	60.5	100.0
Sudan grass (dry matter)	3	27.4	43.7	16.3	59.5	77.0
Sugar beet	5	37.3	56.7	19.4	52.0	71.0

Source: based on research conducted by the Department of Agrochemistry of the Institute of Plant Protection of the National Academy of Agrarian Sciences of Ukraine between 1971 and 2001, with the participation of the authors

Grain yields increased the most when winter wheat was grown after corn – nearly 1.5 times. Even legumes such as soybeans and alfalfa showed yield increases from fertilisation: 24.7% and 31.3%, respectively. The return on investment for each kilogram of active fertiliser ingredient applied was also high. Of course, fertilisers provide higher yield increases when crops are grown on depleted soils that lack sufficient nutrients. This can be seen in the winter wheat grain yields when the crop was planted after alfalfa and MVS corn, where the increases were 65.6% and 147.7%, respectively, compared to the unfertilised control. Irrigation in the Southern Steppe of Ukraine, meanwhile, yields increases ranging from 2 to 5 times higher than in non-irrigated areas and up to 13-15 times higher in extremely dry years, when yields without irrigation are very low or no harvest is obtained at all. Furthermore, irrigated soils exhibit significant changes in key fertility indicators compared to non-irrigated soils (Gamajunova *et al.*, 2021).

Thus, it has been established that within the area served by the Inhulets Irrigation System, in dark

chestnut soil, over the course of four rotations of a 7-field crop rotation including alfalfa (which accounts for 35.7%), annual humus losses from the 0-30 cm layer of non-irrigated soil amount to 70-90 kg/ha, while under irrigation they were significantly higher, particularly in the case of growing crops without fertilisers – 278 kg/ha. The humus content in continuously irrigated soil not only stabilises, but even increases slightly when 80 t/ha of semi-decomposed manure is applied once per crop rotation, along with optimal (recommended) doses of mineral fertiliser (NPK) for each crop – the increase averages 150-200 kg/ha per year. In the Southern Steppe region of Ukraine, the yield of all agricultural crops increases most significantly with the application of nitrogen fertilisers. Nitrogen supply, in particular, is at its lowest among the NPK nutrients across all soil types in this region and has the greatest impact on increasing yield levels. Achieving stable levels of plant productivity on irrigated lands, and consequently a significant removal of nitrogen through harvests, does not ensure a positive balance of this nutrient, even in a crop rotation that includes alfalfa (Table 4).

Table 4. Effects of fertilisers and irrigation on the nitrogen balance in dark chestnut soil over 4 cycles of a 7-field crop rotation*

Variant ^{xx}	Total inputs (including fertilisers, precipitation, irrigation water, fixation by microorganisms, etc.), kg/ha	Total outputs (harvest removal, mineral fertiliser application, etc.), kg/ha	over 4 years of rotation (28 years)	Balance, ± kg/ha	
				on average per crop rotation cycle	on average per year
No irrigation, no fertilisers	1,022.7	2,499.3	-1,476.6	-369.2	-52.7
No irrigation + NPK ₁	2,515.2	3,264.1	-748.9	-187.2	-26.7
No irrigation + NPK ₂	4,214.4	3,716.0	+498.4	+124.6	+17.8
Irrigation, no fertilisers	1,588.9	3,349.7	-1,760.8	-440.2	-62.9
Irrigation + NPK ₁	3,193.6	4,553.7	-1,360.1	-340.0	-48.6
Irrigation + NPK ₂	4,878.1	5,544.7	-666.6	-166.7	-23.8

Note: * – crop rotation sequence: 3-year alfalfa, winter wheat, grain corn, silage corn, winter wheat; ^{xx} – NPK1 – recommended application rate of mineral fertilisers for each crop in the rotation under non-irrigated conditions; NPK2 – recommended application rate of fertilisers for each crop in the rotation under irrigated conditions

Source: developed by the authors

In conditions of increasing aridity, insufficient rainfall, and erratic precipitation patterns, irrigation helps stabilise yields of winter wheat, sunflowers, and winter rapeseed and contributes to increasing the profitability of their cultivation, as confirmed by the findings of other researchers (Markova *et al.*, 2025). In southern Ukraine, on southern chernozem soils during the dry year of 2025, when only 224.2 mm of precipitation had fallen by mid-October and the harvest of most varieties and hybrids of corn, sunflower, soybeans, and other crops in the Mykolaiv region was not collected, these crops yielded 3.2-8.7; 2.2-3.4, and soybeans – 2.1-3.6 t/ha, depending on the number of irrigations and background fertilisation levels. Even in years with the most favourable moisture conditions, applying one or two irrigations at modest rates during critical growth

stages, combined with modern technologies, ensures significant increases in yield. For example, when growing the “Duma Odeska” winter wheat at the Science and Research Center of the Mykolaiv National Agrarian University using the Mzuri Pro-Till technology on irrigated land during the 2022-2023 growing season, a grain yield of 8.18 metric tons per hectare was achieved; using conventional technology, the yield was 13.2% lower. Under natural moisture conditions during the same year, which was quite favourable in terms of precipitation, the “Duma Odeska” winter wheat yielded 5.56 metric tons per hectare of grain, or 47.1% less. The importance of irrigation and the combination of growth-stage irrigation with fertiliser application was also demonstrated in the cultivation of two winter wheat varieties (Table 5).

Table 5. Grain yields of winter wheat varieties under different fertiliser applications and irrigation regimes (average for 2023-2025), t/ha

Irrigation regime (Factor A)	Nutrient optimisation (Factor B)	Crop variety (Factor C)		Average	
		Vidrada	Perlyna Stepu	Factor A	Factor B
Biologically optimal	No fertilisers	4.48	4.53	6.45	4.51
	N ₆₀ P ₃₀ K ₃₀	7.62	7.72		7.67
	N ₃₀ + foliar feeding with a biological preparation	7.18	7.14		7.16
Water-conserving	No fertilisers	4.32	4.36	6.27	4.34
	N ₆₀ P ₃₀ K ₃₀	7.39	7.43		7.41
	N ₃₀ + foliar feeding with a biological preparation	7.03	7.09		7.06
Soil-conserving	No fertilisers	4.43	4.45	6.36	4.44
	N ₆₀ P ₃₀ K ₃₀	7.54	7.57		7.56
	N ₃₀ + foliar feeding with a biological preparation	7.10	7.08		7.09
Average by factor C		6,34	6.37		
HIP ₀₅ , t/ha		by factor A 0.19-0.23 by factor B 0.22-0.28 by factor C 0.17-0.21			

Source: developed by the authors

As indicated by the data obtained on winter wheat grain yield levels, even conservative irrigation ensures

the development of stable grain productivity. It increases significantly when nutrition is optimised compared

to the control. While the average grain yield across all irrigation treatments and both varieties without fertilisers was 4.43 t/ha, it increased to 7.55 t/ha (by 70.4%) with the application of $N_{60}P_{30}K_{30}$, while under the resource-efficient fertilisation system, it was slightly lower – 7.10 t/ha (a 60.3% increase). Certainly, with moderate soil levels of mobile forms of NPK and when winter crops are planted on more depleted preceding crops, grain yields would be lower compared to planting after peas. The results of the studies once again demonstrate the importance of applying fertilisers, which significantly increase the return on irrigation water, and the need to combine these two factors – irrigation and fertilisation.

During the long-term cultivation period from 2021 to 2025, across the five varieties, the average winter wheat grain yield without irrigation was 3.44 t/ha, while under moderate irrigation conditions it was 7.66 t/ha, which is 4.22 t/ha (122.7%) higher. This clearly demonstrates the importance of restoring irrigation across large areas in the Southern Steppe of Ukraine and the fact that, under conditions of climate change, it is impossible to achieve stable crop yields in dry years without irrigation. However, even before the war began in Ukraine, the area of irrigated land had begun to decline, and after the destruction of the Kakhovka Reservoir and the irrigation network, it shrank even further (Table 6).

Table 6. Area of irrigated land in the Oblasts of the southern region as of January 1, 2025, thousand hectares

Oblast thousand ha	Dnipropetrovsk	Zaporizhzhia	Mykolaiv	Odesa	Kherson	Total
Total area of irrigated land	198.7	241.0	190.3	226.9	427.1	1,284.0
Actual irrigated area in 2024	20.1	0	16.5	40.1	0	76.7

Source: summarised by the authors

The data presented in Table 6 indicate a low level of actual utilisation of irrigated land in the southern Oblasts of Ukraine. In 2024, the share of actually irrigated areas relative to their total area was 10.1% in the Dnipropetrovsk Oblast, 8.7% in the Mykolaiv Oblast, and 17.7% in the Odesa Oblast. In the Oblasts experiencing the most intense warfare, Zaporizhzhia and Kherson, not a single hectare was irrigated. The low level of utilisation of irrigated land occurs against a backdrop of rising temperatures, increasing aridity, and erratic precipitation patterns caused by current manifestations of climate change. Under these conditions, the reduction in the area under actual irrigation increases the dependence of crop yields on weather conditions, raises the risk of crop shortfalls, and limits the stability of agricultural production in the southern region of Ukraine. The restoration and efficient use of irrigated land are key to ensuring Ukraine's food security. Practical measures should include the restoration and modernisation of irrigation infrastructure, the repair and reconstruction of on-farm networks, the introduction of water-saving irrigation technology, particularly drip and sprinkler irrigation, as well as the optimisation of irrigation regimes in accordance with crop needs and the availability of water resources. Implementing these measures will help increase yield stability, promote more efficient use of land resources, and reduce risks to agricultural production amid climate change and military challenges.

DISCUSSION

The results of the studies confirm the high effectiveness of combining irrigation with balanced mineral

nutrition for increasing crop yields in the Southern Steppe of Ukraine. The results of the studies confirm the high effectiveness of combining irrigation with balanced mineral nutrition for increasing crop yields in the Southern Steppe of Ukraine. According to the study results, winter wheat yields under moderate irrigation in 2021-2025 averaged 7.66 t/ha, compared to 3.44 t/ha without irrigation, representing a 122.7% increase. At the same time, a water-conserving regime with two irrigations of 450 m³/ha each yielded 7.41 t/ha with the application of $N_{60}P_{30}K_{30}$, i.e., only slightly lower than the biologically optimal regime (7.67 t/ha). This indicates the potential to increase water productivity by optimising irrigation timing and rates. The results obtained are consistent with recent studies in arid and semi-arid regions. A. Abdelfattah & H. Mostafa (2024) noted that deficit irrigation can increase water use efficiency provided that the magnitude and duration of the water deficit are correctly determined. At the same time, the effect depends on the crop and its growth stage: corn is more sensitive to water deficit during flowering and grain formation, whereas in early growth stages, a greater deficit is tolerated without a proportional decrease in yield. For soybeans, F. Morbidini *et al.* (2024), based on a meta-analysis of 25 studies, found that deficit irrigation generally reduces yield but can simultaneously increase water use efficiency; the magnitude of the effect depends significantly on the growth stage during which the water deficit occurs. This confirms the appropriateness of the approach used, in which the water-conserving regime involved irrigation specifically during critical periods of winter wheat development.

The effectiveness of regulating irrigation schedules and regimes is confirmed by the results of a global meta-analysis by N. Ali *et al.* (2024), which established a relationship between yield and water use efficiency and irrigation planning methods under various soil and climatic conditions. The authors demonstrated that optimising irrigation timing and rates is a key tool for increasing the water productivity of crops. An important finding of the studies is the established relationship between water and mineral nutrition. The application of $N_{60}P_{30}K_{30}$ increased winter wheat yield to 7.55 t/ha compared to 4.43 t/ha without fertilisers, i.e., by 70.4%. These results are consistent with those of Y. Li *et al.* (2023), who, under the arid conditions of northwestern China, established a relationship between irrigation regimes and nitrogen nutrition and the efficiency of water and nitrogen use. Optimising these factors helps increase productivity and reduce the risks of nitrate leaching and secondary soil salinisation. The results regarding the nitrogen balance are consistent with international studies. In the arid regions of Ethiopia, it has been found that long-term irrigation affects soil reserves of organic carbon and total nitrogen, while requiring monitoring of soil quality (Weldewahid *et al.*, 2023). Studies conducted in the arid conditions of Egypt also revealed changes in organic carbon, nitrogen, and overall soil quality depending on irrigation practices (Fadl *et al.*, 2024). The results confirmed the need to combine irrigation with a rational organic-mineral fertilisation system to preserve soil fertility. The importance of water-conserving technologies is particularly increasing under conditions of limited water resources. Recent research by C.-M. Geilfus *et al.* (2024) emphasised the need to improve water use efficiency in agricultural production by optimising irrigation regimes, accurately determining plant water requirements, and implementing technologies that enable higher yields per unit of water used.

The results obtained are also consistent with the findings of V. Shebanin *et al.* (2025), who determined the economic viability of the Mzuri-ProTil resource-saving technology. Research by M. Korkhova & A. Panfilova (2024) confirmed the significant impact of moisture levels and mineral nutrition on the productivity of winter wheat varieties. The results of O. Babych (2025) also demonstrated increased crop productivity under controlled irrigation in the Mykolaiv Oblast. At the same time, long-term irrigation requires monitoring not only of the water regime but also of the soil's salinity and nutrient status. Research by X. Guo *et al.* (2023) showed that prolonged use of mineralised irrigation water can alter the soil's physicochemical properties

and biological processes, while M. Fadl *et al.* (2024) emphasised the need to monitor soil quality during long-term irrigation in arid conditions, particularly to prevent soil degradation and secondary salinisation. Therefore, the positive effect of the organic-mineral fertiliser system observed in the experiments should be viewed not only as a means of increasing crop yields but also as a component of long-term fertility management of irrigated soils. Further confirmation of the feasibility of implementing modern technologies in the Southern Steppe of Ukraine was provided by a study by A. Drobitko *et al.* (2024), who determined that the application of innovative approaches in grain crop cultivation, including modern tillage technologies, drip irrigation, and optimal mineral nutrition, ensures a significant increase in yield and the rational use of natural resources even under conditions of severe drought. A. Nasibov *et al.* (2024) found that improving soil fertility in southern Ukraine, including soils damaged by military operations, helps stabilise crop productivity and ensures the development of economically efficient agricultural production.

The reduction in the area actually under irrigation in the Southern Steppe of Ukraine, especially following the destruction of the Kakhovka hydrotechnical infrastructure, increases the dependence of crop yields on precipitation and heightens the risks of instability in agricultural production. In this context, research findings have confirmed the advisability of restoring irrigation based on water-conserving regimes, precise irrigation planning, optimisation of mineral nutrition, and continuous monitoring of soil conditions. Thus, both international and Ukrainian findings have shown that, for the conditions of the Southern Steppe of Ukraine, the promising approach is not simply to increase the volume of irrigation, but to enhance its efficiency by combining regulated irrigation regimes, balanced fertilisation, modern soil cultivation technologies, and monitoring of water and nutrient regimes. The practical implementation of this approach will help increase yield stability, improve the productivity of irrigation water, and preserve soil fertility in the face of future climate change.

CONCLUSIONS

A significant impact of irrigation on crop productivity in the Southern Steppe of Ukraine has been established. According to the results of studies conducted by the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine over a period of 5 to 40 years, depending on the crop, the irrigation index ranged from 2.0 to 3.4. The highest values were observed for grain corn (3.4), alfalfa for green forage

(3.3), and silage corn (3.2), while for winter wheat it was 2.0. Irrigation resulted in a yield increase of 102-235% compared to non-irrigated conditions, depending on the crop. The greatest increase in productivity was observed for grain corn – by 6.71 t/ha (235%), alfalfa for green forage – by 44.8 t/ha (232%), and silage corn – by 44.7 t/ha (220%). This confirmed the decisive role of regulated water supply in determining crop yields under conditions of insufficient and unstable natural moisture. Optimising mineral nutrition significantly increased the efficiency of crop production on irrigated lands. When optimal doses of NPK were applied, winter wheat yields increased by 65.6% following alfalfa, by 147.7% following corn, by 82.3% following grain corn, and by 24.7% following soybeans. Based on average data from four rotations of a 7-field crop rotation, the increase in production was 50.2%. It was found that increased crop productivity under irrigation is accompanied by increased nutrient removal and the need to adjust fertilisation systems. Over four rotations of the 7-field crop rotation, even with the application of the recommended dose of NPK for irrigated conditions, the nitrogen balance remained negative, averaging -23.8 kg/ha per year. Therefore, maintaining high productivity in irrigated agrocenoses requires systematic monitoring of the nutrient balance.

Prolonged irrigation without replenishing organic matter exacerbated humus losses. In dark chestnut soil, in the absence of fertilisers, annual humus losses due to irrigation amounted to 278 kg/ha, whereas applying 80 t/ha of semi-decomposed manure once per crop rotation, combined with optimal doses of NPK, resulted in an average annual increase in humus reserves of 150-200 kg/ha. This indicates the need to combine irrigation with a balanced organic-mineral fertilisation system to preserve soil fertility. Under the conditions of experiments conducted by the MNAU in 2023-2025, water-conserving irrigation regimes resulted in winter wheat yields of 7.06-7.41 metric tons per hectare, depending on the fertilisation system. With the application of $N_{60}P_{30}K_{30}$ the average yield was 7.67 t/ha under the biologically optimal irrigation regime, 7.41 t/ha under the water-conserving regime, and 7.56 t/ha under the soil-conserving regime, confirming the possibility of combining high productivity with the rational use of irrigation water.

In studies conducted by MNAU in 2021-2025, the average winter wheat grain yield under moderate irrigation was 7.66 t/ha, compared to 3.44 t/ha without irrigation. The increase in yield was 4.22 t/ha, or 122.7%. The results confirm the effectiveness of even moderate irrigation in stabilising winter wheat productivity in the Southern Steppe of Ukraine. As of January 1, 2025, the total area of irrigated land in the Dnipropetrovsk, Zaporizhzhia, Mykolaiv, Odesa, and Kherson Oblasts was 1,284.0 thousand hectares, whereas actual irrigation in 2024 was carried out on only 76.7 thousand hectares, or about 6.0% of the available irrigated land. In the Dnipropetrovsk, Mykolaiv, and Odesa Oblasts, the share of actual irrigation was 10.1%, 8.7%, and 17.7%, respectively, while in the Zaporizhzhia and Kherson Oblasts, no irrigation took place. This level of utilisation of irrigated land significantly limited the region's capacity for stable crop production.

Restoring the productive potential of irrigated agriculture in the Southern Steppe requires a comprehensive restoration and modernisation of land reclamation infrastructure, the reconstruction of irrigation networks, the implementation of water-saving technologies, and the optimisation of irrigation regimes and fertilisation systems. Combining these measures will help stabilise crop yields, ensure more efficient use of water resources, preserve soil fertility, and increase the resilience of agricultural production to climate and military risks. Prospects for further research include the scientific justification of water-saving irrigation regimes for the major crops of the Southern Steppe of Ukraine, determining their interaction with mineral and organic nutrition systems, assessing the effectiveness of modern water resource management technologies, and developing adaptive crop cultivation technologies that account for projected climate change and water scarcity.

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Відродження зрошення в Південному Степу є гарантом продовольчої безпеки України

Валентина Гамаюнова

Доктор сільськогосподарських наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Гонґадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-4151-0299>

Ірина Смірнова

Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонґадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-8976-3818>

Любов Хоненко

Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонґадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-5365-8768>

Тетяна Бакланова

Кандидат сільськогосподарських наук, доцент
Державна установа «Миколаївська державна сільськогосподарська дослідна станція Інституту кліматично орієнтованого сільського господарства Національної академії аграрних наук України»
57217, вул. Центральна, 17, с. Полігон, Україна
<https://orcid.org/0000-0002-6699-2693>

Анотація. Метою дослідження було визначити вплив режимів зрошення та систем мінерального живлення на продуктивність сільськогосподарських культур, баланс азоту й показники родючості ґрунту в умовах Південного Степу України. У статті наведено результати стаціонарних польових дослідів, проведених в Інституті зрошуваного землеробства Національної академії аграрних наук України протягом 1971-2011 років залежно від культури на темно-каштанових ґрунтах та Навчально-науково-практичному центрі Миколаївського національного аграрного університету впродовж 2021-2025 рр. на чорноземі південному. У процесі досліджень застосовано загальноприйняті методи польового дослідів, лабораторні та аналітичні визначення, дисперсійний аналіз експериментальних даних. Встановлено, що зрошення є визначальним чинником стабілізації врожайності в посушливому регіоні: приріст урожаю залежно від культури становив у середньому 2-3 рази, а в надзвичайно посушливі роки – до 5 і більше разів порівняно з вирощуванням у богарних умовах. Найвищі індекси зрошення отримано за вирощування кукурудзи на зерно (3,4), люцерни (3,3) та кукурудзи на силос (3,2). Для пшениці озимої поєднання біологічно оптимального режиму зрошення з внесенням рекомендованої дози $N_{60}P_{30}K_{30}$ забезпечило зростання врожайності на 70,4 % порівняно з неудобреним контролем, тоді як водозберігаючий режим поливу також гарантував формування сталої врожайності на рівні 7,0-7,4 т/га. Обґрунтовано, що за зрошення суттєво зростає винесення елементів живлення, особливо азоту, що без його компенсації формує від'ємний баланс у ґрунті. Стабілізація та приріст гумусу (150-200 кг/га щорічно) досягалися лише за застосування органо-мінеральної системи удобрення в сівозміні з внесенням гною та оптимальних доз мінеральних добрив. Отримані результати підтвердили доцільність поєднання зрошення та збалансованого удобрення для підвищення продуктивності культур, ефективності використання води й збереження родючості ґрунтів, що створює наукові передумови для модернізації зрошувальних систем Південного Степу України в умовах кліматичних змін

Ключові слова: кліматичні зміни; режим зрошення; система удобрення; баланс азоту; родючість ґрунту; пшениця озима