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Fertigation with sprinklers: Food and water security on the Ukrainian steppe

Dmytro Onopriienko[1], Hennadii Hapich[1*], Andrij Tkachuk[1], David Dent[2], Volodymyr Kovalenko[1], Tetiana Makarova[1], Hynek Roubik[3]

[1] Dnipro State Agrarian and Economic University, 25 Serhiy Yefremov St, Dnipro, 49009, Ukraine
[2] Independent Scientist, Norfolk, United Kingdom
[3] Czech University of Life Sciences Prague, Kamýcká 129, Prague, 16500, Czech Republic
* Corresponding author's e-mail: hapich.h.v@dsau.dp.ua

ABSTRACT

Facing climate change, soil degradation and sabotage of one third of the country's freshwater resources (due to the war and destruction of the Kakhovka reservoir), the prospects of fertigation on black soils in the south of Ukraine using sprinkler irrigators were examined. By compiling daily soil hydrographs, it is possible to track changing water availability and control the soil water regime to ensure irrigation efficiency, preserve soil condition, and boost yields. Fertigation enables a more uniform distribution of fertilisers across the field compared to conventional broadcasting, and supplies nutrients during critical stages of crop growth when the size of the crop excludes wheeled vehicles. Comprehensive management of soil water and nutrient supply throughout the growing season yielded 16–17 t/ha of grain corn; the water-use coefficient was 344 m^3/t; total water consumption reached 5670 m^3/ha, of which 2900 m^3/ha was irrigation.

Keywords: fertigation, fertiliser, irrigation, food security, water security, corn, Ukrainian steppe**.**

INTRODUCTION

Burgeoning demand for agricultural commodities requires the same increase in production, but farmers face increasing competition for water resources and irrigation already takes the lion's share of abstracted water (Hoogeveen et al., 2015, Polevoy et al., 2024). Maize is a large recipient (Erenstein et al., 2022) and because its growing season is extended by irrigation, so are its nutrient requirements (Vozhehova et al., 2019). Integration of fertilisation and irrigation will enable greater productivity with fertilisers contributing as much as 70 per cent of the yield increase (Kiver and Onopriienko, 2016), but maximum output and top quality depend on maintaining the land in good condition (Pichura et al., 2023).

Uneven fertiliser application is hard to remedy (Li et al., 2018); and use of heavy machinery for surface dressing compacts the soil, reduces yields and increases the costs of subsequent cultivation (Keller et al., 2019, Shevchenko et al., 2024). At the same time, conventional dry fertiliser application leads to substantial losses: nitrogen compounds can transform into gaseous ammonia or nitrogen oxides, nitrates leach all too readily to the groundwater, phosphates are carried in surface runoff to streams; together with mineralised irrigation water, all these contribute to soil and water salinity, especially under irrigation (Onopriienko et al., 2023, 2024). These problems can be mitigated by *fertigation* (Kopittke et al., 2019) – i.e. application of fertiliser with irrigation water taking into account of the crop's growth and development stages, soil attributes, water quality, and the compatibility and solubility of different fertilisers. In short, fertigation resolves the distribution of fertiliser and any other agrochemicals according to the 4R principles: right source, right rate, right time, and right place (Fixen, 2020).

Previous studies (Kiver and Onopriienko, 2016, Onopriienko, 2020) have shown that both liquid and water-soluble solid fertilisers produce only minimal sludge, do not cause significant corrosion and are, therefore, suitable for use in fertigation. A global meta-analysis of fertigation with surface and drip irrigation (Delbaz et al., 2023) showed equally positive effects on yields, increasing them by 20%. Moreover, an economically and environmentally significant reduction of the fertiliser dose to 75% of recommended levels has no significant impact on yields. In Ukraine, fertigation of specialist fruit and vegetable crops by drip and underground irrigation is well established (Romaschenko et al., 2012, Tsurkan et al., 2021), but multipurpose use of sprinkler machinery for fertigation of staple crops has been neglected (Sidorenko, 2021). Now, beyond the inexorable increase in evaporative demand and declining rainfall across the steppes (Lykhovyd, 2021), the loss of more than one-third of the country's freshwater reserves by destruction of infrastructure demands application of the best domestic and international experience and modern technologies to increase crop yields and safeguard the environment (Hapich et al., 2023; Dovhanenko et al., 2024; Pichura et al., 2024). The fact that most of the water needed for the rest of the century currently flows down the Danube is no longer the technical problem that it used to be (Romaschenko et al., 2025).

The research objective was to study the optimal rates, methods and timing of applying mineral fertilisers under sprinkler irrigation for intensive corn production.

MATERIALS AND METHODS

Research was conducted in 2019 on a 62 ha irrigated field at Preobrazhens'ke LLC (Limited Liability Company) in Zaporizhzhia province.

Figure 1 shows the general climatic characteristics of Ukraine. The study site lies within the southern Steppe zone of lowest precipitation and highest accumulated temperature during the growing season. Irrigation is indispensable to high and stable crop yields; and an extensive network of canals and pipelines was constructed in the mid-20th century (1950–1980) encompassing more than one million hectares (Hapich and Onopriienko, 2024) making it the largest cluster of irrigated land in Europe, dependent on the Kakhova Reservoir that was destroyed in 2023. The terrain is essentially flat but with a microrelief

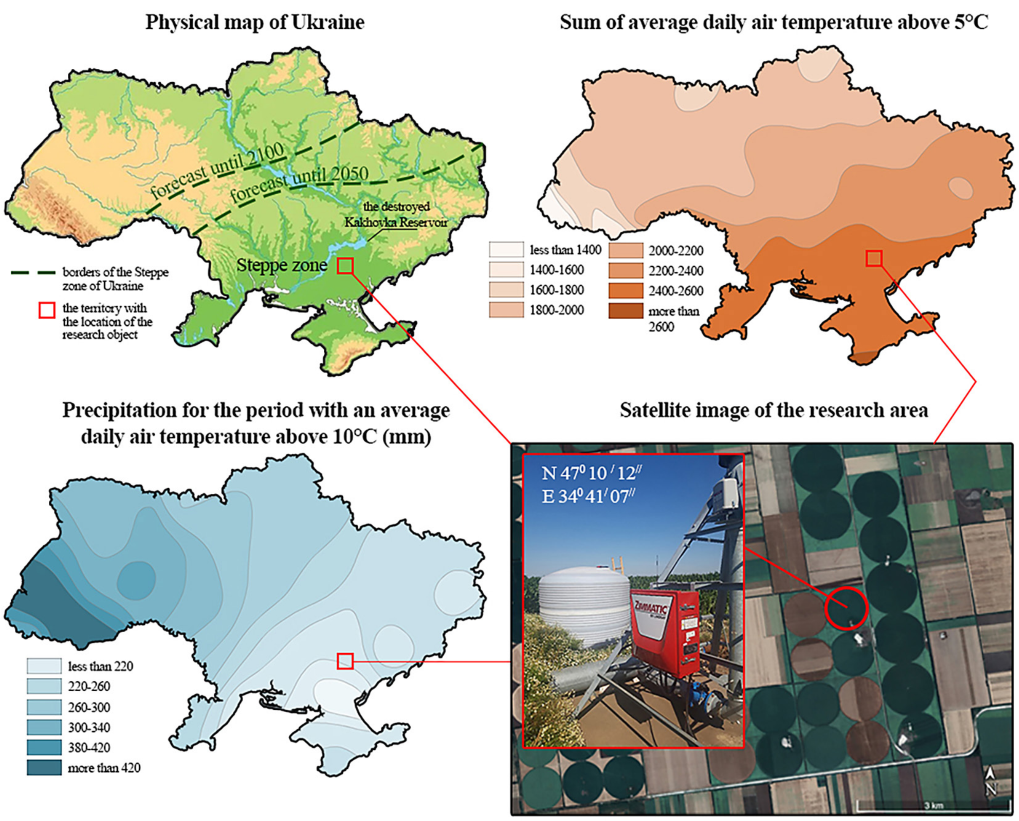

Figure 1. Climatic features of Ukraine's steppe zone and overview of the research site, including the sprinkler equipment and the tank used for mixing fertilisers with irrigation water

of closed depressions. The groundwater table lies 8–10 m below the surface. The soil is low-humus *Southern chernozem*; the analysis showed a loamy texture in the 0–40 cm layer with 25.8–26.8% clay. At the outset, the agronomic team at Preobrazhenske LLC collected composite soil samples from different depths to determine the humus content, macro- and micronutrients and, specifically to support fertigation technology, particle-size distribution, dry bulk density and field capacity (Tables 1 and 2).

The proportion of the most agronomically valuable aggregates (0.25–1.00 mm) in the 0–20 cm layer was 70%, increasing to 74% in the 20–40 cm layer. Water infiltration and percolation were satisfactory: the infiltration rate in the tilled layer was 2.3–2.6 mm/hour, transitioning to percolation after two to three hours, although in terms of natural moisture levels, the soil is classified as having low water availability.

The late-maturing Pioneer P9911 corn hybrid that maximises water use and responds well to irrigation was selected. Sowing at 90 000 seeds/ha was carried out with a John Deere 8320RT tractor coupled to a Väderstad Tempo L precision planter. The preceding crop was winter rapeseed.

Irrigation water was supplied from the Kakhovka Reservoir via the Pivnichno-Rohachytska irrigation system. Comprehensive chemical analysis of the irrigation water using 34 parameters, 12 of which are presented in Table 3, confirmed its suitability for agricultural irrigation without risk to the environment. Urea-ammonium nitrate solution UAN-32 (32% nitrogen) was used as nitrogen fertiliser, offering several advantages over solid nitrogen fertilisers (Klimczyk et al., 2021, Ren et al., 2023). The application rate was determined according to the soil analysis, the requirements of the crop and the target yield.

The irrigation regime was established by tracking daily soil moisture reserves and deficits (Zaporozhchenko et al., 2022, Tkachuk et al., 2023) as well as, simultaneously, real-time thermogravimetric monitoring of soil moisture. The ideal soil water status for corn-for-grain is within 70% of field capacity – field capacity being the upper limit of the soil's water-holding capacity (WHC) under free drainage. The irrigation rate was determined by considering the soil's physical properties and structure, the depth and degree of wetting, as well as the irrigation equipment, according to the formula:

Table 1. Agrochemical characteristics of the soil at the research site

Sample No.	Sampling depth (cm)	$N\text{-}NO_3$, mg/kg			P_2O_5 mg/kg	K_2O mg/kg	Humus %
		$N\text{-}NO_3$ (Kravkov)	$N\text{-}NO_3$ (Kornfield)	Ammonium			
1	0–40	51.2	17.9	11.3	151	150	1.25
2	0–40	52.4	16.8	11.5	150	163	1.20
3	0–40	53.3	17.3	11.8	151	138	1.25
4	0–40	52.5	12.2	11.3	150	194	1.10
Average	0–40	52.4	17.8	11.4	150	149	1.2

Table 2. Water-physical properties of the soil at the research site

Soil layer (cm)	Bulk density (g/cm³)	Specific gravity (g/cm³)	Field capacity, %	
			By mass	By volume
0–10	1.37	2.50	19.9	27.3
10–20	1.41	2.48	19.1	25.8
20–30	1.41	2.44	18.4	24.1
30–40	1.36	2.49	18.4	24.7
40–50	1.29	2.44	18.4	24.0
50–60	1.31	2.46	18.5	24.8
60–70	1.29	2.48	18.6	24.2
70–80	1.32	2.50	18.6	24.5
80–90	1.32	2.50	18.6	24.5
90–100	1.32	2.50	18.5	24.3

Table 3. Chemical analysis of irrigation water

No.	Indicator	Analysis result
1	Temperature, °C	12.6
2	Turbidity, mg/dm³	2.2
3	Reaction, pH	8.0
4	Suspended solids, mg/dm³	2.5
5	Dry residue, mg/dm³	345
6	Alkalinity, meq/dm³	35
7	Hardness, meq/dm³	4.2
8	Calcium, mg/dm³	58.8
9	Magnesium, mg/dm³	15.0
10	Sulphate, mg/dm³	78.3
11	Chloride, mg/dm³	30.7
12	Ammonium, mg/dm³	0.3

$$m = 100 \cdot \mathrm{H} \cdot \gamma \cdot (\beta_{WHC} - \beta_{per}) \quad (1)$$

where: H is the depth of the soil layer under calculation (m); γ is the bulk density of the calculated soil layer (g/cm³); β_{whc} is the soil moisture content at field capacity (WHC, %); β_{per} is the soil moisture content at the permissible (lower) drying limit (%).

Effectiveness of soil moisture use was evaluated using mean daily evaporation:

$$e = \frac{E}{T} \quad (2)$$

where: E is the total evaporation over the calculation period (mm); and T is the duration of the calculation period (days).

Total water consumption over the corn growth and development periods was calculated by water balance:

$$E = \Sigma IW + P + \Delta W \quad (3)$$

where: E is the total water consumption over the calculation period (m³/ha); ΣIW is the irrigation water applied during the growing season (m³/ha); P is the atmospheric precipitation (m³/ha); and ΔW is the change in soil water reserves (m³/ha).

The water-use coefficient was determined by:

$$C_w = T_w / Y \quad (4)$$

where: C_w is the water consumption coefficient (dimensionless); T_w is the total water expenditure (t/ha); and Y is the yield of the main and by-products (t/ha dry mass).

The normalized difference vegetation index (NDVI) was used to assess plant development and health:

$$NDVI = (NIR + RED)/(NIR + RED) \quad (5)$$

where: NIR is reflectance in the near-infrared range of the spectrum and RED is reflectance in the red range.

RESULTS

Table 4 presents the fertiliser requirements for the target yield, calculated using the balance method, according to the corresponding nutrient content in the 0–40 cm soil layer; the measured levels of mobile nutrients in the soil; the total reserve of nutrients in this layer; the coefficient of nutrient use from the soil; the amount of nutrients taken up by the plants and, consequently, the additional nutrients required from fertilisers; the coefficient of

Table 4. Calculation of mineral fertiliser rates for a target yield of 16t P9911 corn grain/ha

No.	Balance component	Nutrient		
		N	P_2O_5	K_2O
1	Nutrient removal for the target yield, kg/ha	230	100	210
2	Nutrient content in the 0–40 cm soil layer, mg/kg	52.4	150	150
3	Total nutrient content in the 0–40 cm layer, kg/ha	22.4	641	641
4	Coefficient of nutrient use, %	80	15	40
5	Amount of nutrients absorbed from soil, kg/ha	17.9	96	256.4
6	Additional nutrients required from mineral fertilisers, kg/ha	86.2	4.0	-
7	Coefficient of nutrient utilization from mineral fertilizers, %	50	25.0	65
8	Nutrients supplied via mineral fertilizers, accounting for use, kg/ha	149.8	-	-
9	Form of mineral fertilizers, UAN 32 (liquid)	-	Superphosphate	-
10	Active ingredient content, %	32	48	-
11	Total nutrients applied, kg/ha	468	-	-

nutrient use from mineral fertilisers; the amount of nutrients delivered via fertilisers after factoring in this coefficient; the specific kinds of mineral fertilisers; the percentage of active ingredient in the fertiliser; and hence the quantity of fertiliser required.

According to the calculation, the planned corn yield would require 468 kg/ha of nitrogen fertiliser. The crop was fully supplied with phosphorus, since 200 kg/ha of superphosphate was incorporated during autumn ploughing in October 2018. In addition, 60 kg/ha of anhydrous ammonia was applied in spring 2019 (March 6th, 2019), followed by a broadcast of 140 kg/ha of urea (March 14th) prior to harrowing, 100 kg/ha of ammonium sulphate (April 25th), and 100 kg/ha of NPK_{16} during sowing (April 29th). Therefore, adding 300 kg/ha of UAN32 through irrigation water would be enough.

In establishing the irrigation regime, the lower limit of the optimal moisture in the soil layer exploited by the crop roots was considered. During critical stages of corn growth and development, the soil moisture in this layer before irrigation exceeded the wilting point by 20–35% of field capacity. Long-term studies on corn water consumption under irrigation confirm the need to maintain specific soil water levels in the root zone (Table 5).

The lower limit of pre-irrigation soil water content was set at between 70 and 75% of field capacity, depending on the corn growth phase. The depth of the main root zone was selected according to regional recommendations while also taking into account the plant's growth periods. For this soil type, the values of β_{WHC} and β_{per} are presented in Table 6.

According to formula (1), irrigation aimed to maintain soil water in the calculated layer above the permissible drying limit and within field capacity for each corn growth phase, accounting for changes in the depth of the root zone. Under sprinkler irrigation, the net irrigation rate must also factor in rainfall intensity, the soil's water absorption capacity, and topography, so as not to exceed the early-onset (erosion-safe) limit. The calculated irrigation rates for different growth phases were: BBCH 00-09, 250 m³/ha; BBCH 10-39, 300 m³/ha; and BBCH 40-59 and BBCH 60-89, 400 m³/ha.

The irrigation regime was set according to the soil water level before irrigation. The specific irrigation dates were determined using the fragmentary hydrograph (Fig. 2) by comparing the actual soil water reserves in the root zone with the soil water threshold for pre-irrigation, as indicated in Table 7. The lower soil water threshold varies depending on the depth of the root zone according to the phenological phase of corn development; *i.e.* an increase in the threshold value is associated with the deeper root penetration as the crop progresses through its growth stages.

The fragmentary hydrograph of daily soil moisture reserves was constructed for different soil layers, taking into account the phenological phases of corn development and the uneven water consumption during the growing season. It displays changes in water reserves in various soil layers, as well as the distribution of rainfall and irrigation rates as histogram. The hydrographs show the dates of irrigation events and the changes in soil water reserves depending on the weather and irrigation. In 2019, three irrigations at a rate of 300 m³/ha and five irrigations at a rate of 400 m³/ha were scheduled and conducted to maintain soil water levels at 70-75-75-70% of field capacity. The total irrigation norm

Table 5. Lower limit of optimal soil moisture in the field

Phenological growth stage of corn	Root penetration depth (m)	Soil water corresponding to permissible drying limit, % of field capacity
BBCH 00-09	0.5	70%
BBCH 10-39	0.7	75%
BBCH 40-59	0.8	75%
BBCH 60-89	0.8	70%

Table 6. Values of bulk density, β_{WHC} and β_{per} by corn growth phases

Phenological phase of corn (BBCH)	Depth of calculated soil layer (m)	Bulk density of calculated layer (g/cm³)	Soil water, %	
			β_{WHC}, %	β_{per}, %
BBCH 00-09	0.5	1.36	25.18	17.63
BBCH 10-39	0.7	1.34	24.98	18.74
BBCH 40-59	0.8	1.34	24.92	18.69
BBCH 60-89	0.8	1.34	24.92	17.44

Table 7. Determining the lower soil moisture threshold by corn growth phases

Phenological phase	BBCH 00-09	BBCH 10-39	BBCH 40-59	BBCH 60-89
Depth of calculated soil layer (m)	0.5	0.7	0.8	0.8
Field capacity, %	25.18	24.98	24.92	24.92
Lower soil water threshold before irrigation, % field capacity	70	75	75	70
Permissible soil drying limit, %	17.63	18.74	18.69	17.44

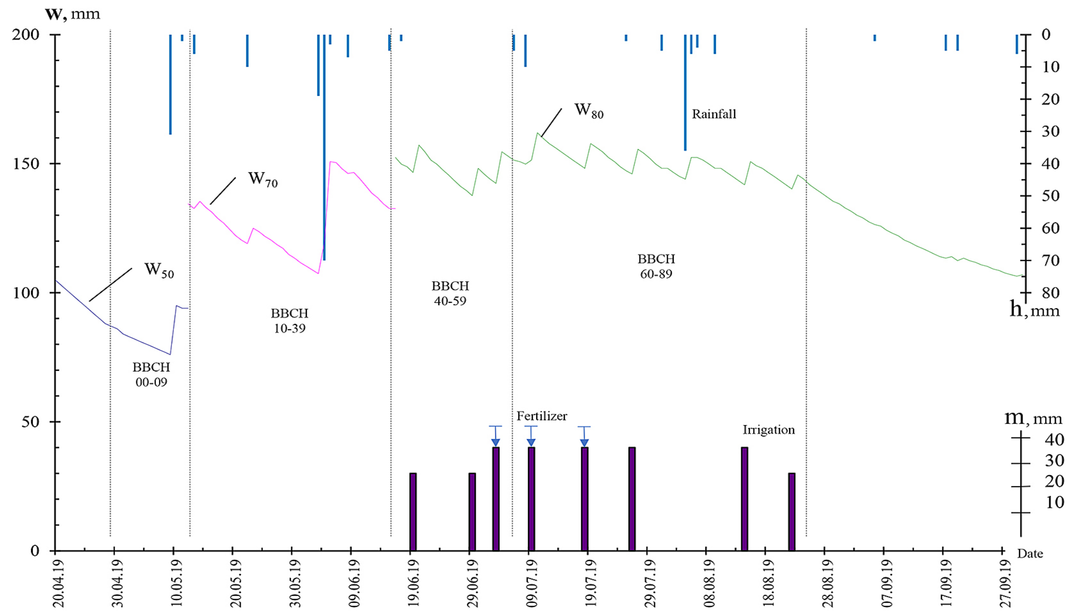

Figure 2. Fragmentary hydrograph of soil water reserves with the irrigation regime for grain corn: h – precipitation; m – irrigation rate; $W_{50\text{-}70\text{-}80}$ – soil water reserves at depths of 50, 70 and 80 cm, respectively

amounted to 2900 m³/ha (Table 8). Additionally, in 2019, three fertilising irrigations were performed during the corn's critical growth periods, with an irrigation rate of 400 m³/ha. Along with the irrigation water, 300 kg/ha of UAN32 fertiliser was applied. The crop's water consumption over time regulates the uniformity of crop emergence, the intensity of root system development, the growth of the aboveground biomass and the subsequent grain yield. Thus, observations were conducted on water consumption during the main phases of corn development. The growing season was divided into four main periods to which the dynamics of water consumption were correlated. The values of average daily and total water consumption are presented in Table 9 and illustrated in Figure 3. The highest average daily water consumption is 51–53 m³/ha during the BBCH 40–89 phase of development (62.8%). The curve of total water consumption shows the first, second, and fourth phases exhibit similar dynamics in water demand but, in the third phase, there is a noticeable steepening of the curve that corresponds to the plant's critical stage of development stage and highlights the significance of meeting the crop's water requirements during this phase to ensure optimal growth and yield. Table 10 summarises crop water consumption during the growing season.

Water consumption during the period from sowing to emergence was mainly evaporation from the soil surface; the plant's water needs were minimal and average water consumption was approximately 32 m³/ha. In the period from emergence to tasselling, when the root system developed intensively along with the above-ground biomass, transpiration increased significantly and water consumption was 1.5–2.0 times higher compared to the initial phase of development. Under irrigation, the average daily transpiration of corn reaches its peak during the interphase period from the onset of tasselling to the milk stage of kernel development and adequate water supply during this stage is critical to support optimal plant growth and maximise yield. Harvest yield assessment was carried out by weight in four replicates per plot. It is presented in Table 11. On average, the yield of corn grain at 17.6% moisture content

Table 8. Corn irrigation regime at the research field

Irrigation No.	Date	Irrigation rate, m³/ha	Fertilising irrigation (fertilizer dose)	Total irrigation norm (ΣIW), m³/ha
1	19.06.2019	300	None	2 900
2	29.06.2019	300	None	
3	03.07.2019	400	UAN 100 kg/ha	
4	09.07.2019	400	UAN 100 kg/ha	
5	18.07.2019	400	UAN 100 kg/ha	
6	26.07.2019	400	None	
7	14.08.2019	400	None	
8	22.08.2019	300	None	

Table 9. Average daily and total water consumption of corn

Phenological phase	Average daily water consumption, m³/ha	Total water consumption, m³/ha	% of total seasonal consumption
BBCH 00-09	30.8	400	7.0
BBCH 10-39	36.4	1200	21.2
BBCH 40-59	53.0	1060	18.7
BBCH 60-89	51.0	2500	44.1
BBCH 90-99	14.6	510	9.0
Total		5670	100.00

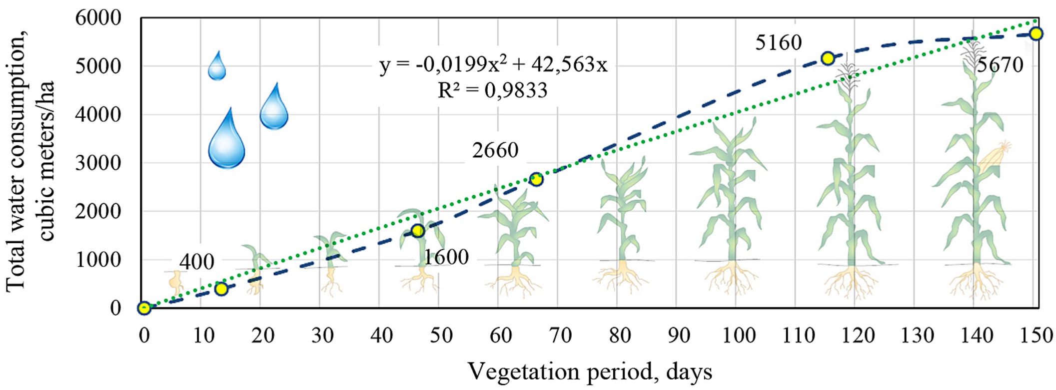

Figure 3. Total water consumption of corn across phenological development phases

Table 10. Corn water consumption during the growing season

Elements of total water consumption and share in total consumption						Total water consumption	
Soil moisture reserves ($W_{initial}$-W_{final})		Rainfall during the growing season		Irrigation during the growing season			
m³/ha	%	m³/ha	%	m³/ha	%	m³/ha	%
300	5.3	2470	43.6	2900	51.1	5670	100.0

Table 11. Biological yield assessment for corn grain (harvest date: October 3, 2019)

Plot No.	Harvested area, m²	Weight of marketable produce (kg)	Weight of main produce portion (kg)	Yield of main produce portion, centners/ha at 17.6% moisture	Grain yield at 13% moisture, centners/ha
1	10	18.71	4.61	159.0	152.6
2	10	19.76	4.61	167.9	161.18
3	10	20.95	4.53	178.0	170.8
4	10	21.67	4.53	184.1	176.7
Average	-	-	-	172.2	165.32

was 17.2 t/ha, while the yield adjusted to 13% moisture content amounted to 16.5 t/ha. Given the total water consumption of 5 670 m³/ha, the water consumption coefficient calculated using formula (4) was 343.6 m³/t.

DISCUSSION

In the face of climate change and war, the steppes are at risk of desertification and depopulation (Hapich et al., 2024a, 2024b, Sudakov et al., 2025): restoration of Europe's largest cluster of irrigated lands is urgent (Rosa et al., 2023, Hapich and Onopriienko, 2024, Romashenko et al., 2025). At the same time, smart investments in modern farming technologies and AI-driven systems could transform the country and, as Keulertz et al. (2024) suggest, Ukraine's integration into the European Union could make the EU as the world's largest supplier of agricultural commodities.

Across the southern steppes, rainfed corn yields 3–5 t/ha in an average year but, in dry years, fields are often disked as early as June, because harvesting is not worthwhile. Irrigation offers food security and economic stability and fertigation harmoniously delivers nutrients with water and distributes them more uniformly in the root zone than by other means. Fertiliser efficiency increases through lesser applications per unit of production and less leaching, gaseous losses and immobilisation, whereas fertigation causes less soil compaction and mechanical plant damage. Nutrients are in an immediately available form and nutrient content, and ratios can be tailored to the specific needs of crops at different growth and development phases, while their environmental impact is minimised because the solutions used at low concentration (0.1–0.5%) (Azad et al., 2020, Klimczyk et al., 2021). There is also worthwhile savings of time, labour and energy (Kabirigi et al., 2017). The cons are additional costs for equipment to dissolve, dose and introduce nutrients into the irrigation water flow and the need for highly qualified staff.

All mineral fertilisers, especially nitrogen-based fertilisers are somewhat corrosive, and improper mixing or incomplete dissolution produces a sludge, so, careful attention is necessary. Most nitrogen and potassium fertilisers dissolve well in water, but they are costly and the range is limited. Fertigation is mostly used to apply macronutrients (nitrogen, phosphorus, and potassium); micronutrients are generally applied via foliar sprays in small volumes (Bernert et al., 2015). In practice, it is necessary to account for the rate and duration of injecting and transporting various nutrients, the technology of irrigation, water distribution uniformity, and the actual nutrient content in the soil (Russo, 2016). After fertigation, it is crucial to flush the system with clean water for 10–15 minutes to prevent clogging and corrosion. Although there are many proposed approaches (so-called protocols), there is a shortage of experimental data or mechanism-based evidence regarding optimal fertiliser application in fertigation systems (Bar-Tal et al., 2020, Meng et al., 2023).

The three most common fertigation practices are: (1) supplementary fertiliser application to complement the main application; (2) partial fertiliser application – some nutrients are applied at the early stages of plant growth and development using traditional broadcast or row application, while most of the nutrients are introduced in solution with irrigation water throughout the growing season; (3) full fertiliser application – the entire calculated dose of nutrients is applied with irrigation water over the entire growing season.

Fertilisers can also be applied with irrigation water before sowing during moisture-replenishing irrigations, or, in a dry spring, during emergence-provoking irrigation but the mainstay of fertigation is vegetative irrigation that aims to fully meet the crop's needs for both water and nutrients. The best results are achieved when fertigation aligns with the periods of peak crop nutrient demand and best practice requires combined schedules for irrigation and fertiliser application specifying the timing and doses of nutrients, irrigation rates, and the quantities of mineral fertilisers needed to prepare nutrient solutions at different concentrations, taking into account the available irrigation equipment (Behera and Panda, 2009).

The conducted research also demonstrates the highest efficiency of fertiliser application with irrigation water during the most critical phase of corn development. Sentinel-2A satellite imagery demonstrates a uniform distribution of nitrogen fertilisers within the irrigated field (Fig. 4). The NDVI data indicate that maximum vegetative development of the crop was ensured by 3 irrigations with the full calculated rate of application of nitrogen fertiliser. In fact, the percentage distribution of vigorous plants with an index of 0.7–0.9 increased from 60% in June to almost 98 in August. This confirms the expediency and effectiveness of

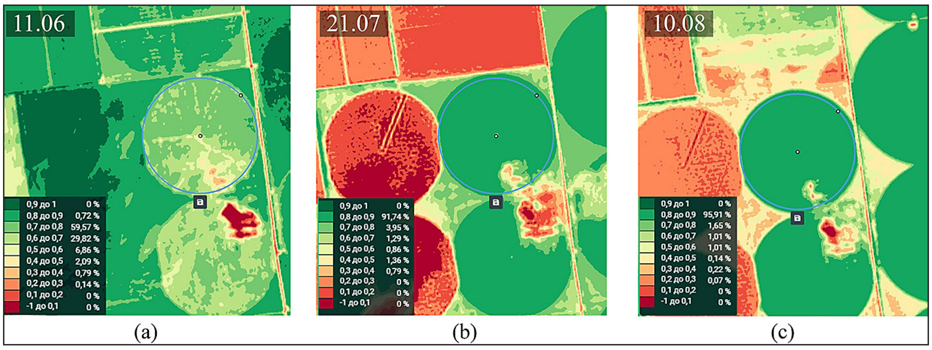

Figure 4. Satellite images of the research field (blue circle in the central part) with NDVI before (a, 11.06), and after (b, 21.07, and c, 10.08) fertigation

fertigation because, in development phase BBCH 40-89, the height of the corn renders other methods of fertiliser application impractical. The maximum permissible concentrations of fertiliser solutions are determined by the phases of plant development, weather, the kind of fertiliser, as well as the frequency of supplying these solutions to the irrigation water (Onopriienko, 2020). Urea solution, even at a nitrogen concentration of about 1%, does not damage corn plants whereas ammonium nitrate can cause burns. Young plants are more sensitive to fertiliser concentration and hot and dry weather, so it is necessary to maintain a lower concentration of nutrients compared to cool and wet weather: the maximum allowable concentrations of nutrients in irrigation water should not exceed 0.5% for nitrogen fertilisers, 2% for phosphorus, 2–3% for potash, and 0.5% for multi-component solutions.

In modern drip irrigation systems, fertilisers are added to the irrigation water using a fertiliser mixing unit, an injector and a pump-doser (Delbaz et al., 2023). Only very soluble fertilisers are used to avoid clogging of the system and clogging of the drippers themselves. The advantages of the system include (Frolenkova et al., 2020), accurate and effective application of fertilisers together with irrigation water; minimal unproductive water loss in any weather, and no leaf scorching. In Ukraine today, the area of drip irrigation is about 40–45 thousand ha and is increasing as the cost of water has increased. As it was shown, it is also possible to apply agrochemicals together with irrigation water to staple, broadacre crops using by sprinklers with the addition of dosing pumps to machines currently operating in Ukraine (Bauer, Valley, Reinke, Zimmatic, etc.). This allows for the complete mechanisation of nutrient supply to the crop.

The research findings can be used wherever irrigated agriculture is practised. The main reasons why 85% of farmers in Ukraine and Europe switch to using urea-ammonium nitrate (UAN), including on irrigated land, are:

- the low cost of nitrogen in UAN;
- low nitrogen losses – less than 10%, while with solid granular nitrogen fertilisers these losses range from 30 to 40%;
- simpler and more efficient logistics – less time spent on loading, transporting and applying;
- lower costs of applying UAN together with irrigation water, microfertilisers and pesticides;
- the possibility of using UAN at different stages of plant development;
- simultaneous root and foliar nutrition of plants through the leaf surface by amide nitrogen, and through the root system by nitrate and ammonium nitrogen;
- the use of fertigation saves 0.5–0.6 kg/ha of fuel, an 8.5 per cent reduction per 1 tonne of corn grain yield compared to dry surface spreading of fertilisers.

It should be noted that about 90% of irrigated land in Ukraine is irrigated by sprinklers and only 10% is irrigated by drip irrigation systems (Romaschenko et al., 2023). On the basis of the research (Romaschenko et al., 2025) and data from the State Agency of Water Resources of Ukraine, Table 12 presents the potential for fertigation in irrigated agriculture in Ukraine. It is also worth noting that the balance capacity (land on the state's balance sheet, which has been certified and has a book value as of today) of Ukraine's irrigation systems is about 1.8 million hectares. Given the availability of water resources and investments in infrastructure, the territory of Ukraine (including the occupied south-eastern regions and Crimea) has great potential for restoring irrigation systems and intensifying agricultural production (Nasibov et al., 2024; Satyr et al., 2024).

Table 12. Potential for the development of fertigation in the steppe zone of Ukraine

Names of basin offices (BO) and regional offices (RO) of water resources (WR) in the steppe zone of Ukraine with developed irrigation systems infrastructure	Estimated irrigated area, thousand ha (as of the year of the study)	Irrigated area under sprinklers, thousand ha (90% of total)	Irrigation by sprinkler with 75% of the land irrigated, thousand ha (optimistic forecast)	Irrigation by sprinkler with 50% of the land is irrigated, thousand ha (pessimistic forecast)
BOWR of the lower Dnipro	309	278	209	139
ROWR Mykolaiv Oblast	32	29	22	14
BOWR rivers of the Azov Sea	53	48	36	24
BOWR rivers of the Black Sea and the lower Danube	38	34	26	17
ROWR Dnipropetrovsk Oblast	29	26	20	13
Other districts	34	31	23	15
Total	495	446	334	223

CONCLUSIONS

During the growing season at the research site in southern Ukraine, evaporative demand greatly exceeds rainfall but, with full implementation of fertigation, corn hybrid P9911 can yield 16–17 tonnes grain/ha. During critical plant growth phases when crop demand is greatest, the height of the crop makes access by agricultural machinery impractical but irrigation water combined with dissolved fertilisers ensures a uniform nutrient supply.

Using daily soil moisture hydrographs enables tracking soil moisture dynamics, controlling soil water in different soil layers, and accounting for other variables. This approach promotes efficient use of water, preserves soil condition, and increases agricultural productivity. Under the conditions of the conducted research, the irrigation rate ranged from 300–400 m³/ha; total water consumption (including rainfall) during the study period was 5670 m³/ha of which 2900 m³/ha was irrigation water; and through fertigation, the target corn grain yield of 16.5 t/ha was achieved with water consumption coefficient of 344 m³/t.

To improve the competitiveness and environmental sustainability of agriculture in drylands, future research on agrotechnology for programmed grain yields should focus on energy and resource conservation at every stage of the technological cycle: tillage, fertiliser application, hybrid selection, calculation of water-saving irrigation regimes, as well as selection of irrigation methods and equipment.

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