

CORN GROWING PRACTICES ON CLAY SOILS UNDER DRIP IRRIGATION IN THE STEPPE ZONE OF UKRAINE

PRATIQUES DE CULTURE DU MAÏS SUR SOLS ARGILEUX SOUS IRRIGATION GOUTTE À GOUTTE DANS LA ZONE STEPPIQUE DE L'UKRAINE

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ABSTRACT

Field experiments evaluating the effectiveness of surface and subsurface drip irrigation of corn were conducted on clay soils in the Steppe zone of Ukraine under increasing natural moisture deficit. The studied soils have low nitrogen availability, a narrow range of moisture available to plants (90–100% of field capacity), and hydraulic conductivity at –3 kPa below 1.9 cm/day. These properties make crops highly sensitive to suboptimal moisture conditions and necessitate the use of capillary potential to regulate irrigation within the available moisture range. During three years of research several values of pre-irrigation threshold (–20, –40, and –60 kPa) and fertilizer application were studied. It was determined that at the threshold of –40 and –60 kPa, plants failed to compensate for water deficits under frequent atmospheric droughts in the studied conditions. The highest yields were obtained at a pre-irrigation threshold of –20 kPa. Regarding fertilization, with a pre-sowing application of N55.5P25.5K25.5 kg/ha of active substances, treatments included no additional fertilizer application and supplemental fertigation of N80.5P0K44.2, N128.3P1.8K90.2, and N202.9P18.9K161.9 kg/ha of active substances. Yields increased from 9.42 t/ha without additional fertilization to 11.24 t/ha at maximum application, with a correlation coefficient for the dependency between yield and fertigation amount equal to 0.79. Our results confirm the high efficiency of drip irrigation and the applicability of capillary potential for determining irrigation rates and schedules in the studied conditions. However, with high frequency of atmospheric droughts, on clay soils drip irrigation cannot maintain the evapotranspiration required to achieve potential hybrid productivity, primarily due to the inability to form a favorable near-surface air microclimate, which also reduces nutrient use efficiency.

Keywords: drip irrigation; fertigation; corn; clay soils; Ukraine.

RÉSUMÉ

Des essais au champ visant à évaluer l'efficacité de l'irrigation goutte à goutte de surface et souterraine du maïs ont été menés sur des sols argileux de la zone steppique de l'Ukraine, dans un contexte d'accentuation du déficit hydrique naturel. Les sols étudiés présentent une faible disponibilité en azote, une plage étroite d'humidité disponible pour les plantes (90 à 100 % de la capacité au champ) et une conductivité hydraulique à –3 kPa inférieure à 1,9 cm/jour. Ces propriétés rendent les cultures très sensibles aux conditions d'humidité sous-optimales et imposent l'utilisation du potentiel capillaire pour réguler l'irrigation dans la plage d'humidité disponible. Au cours de trois années de recherche, plusieurs valeurs du seuil de déclenchement de l'irrigation (–20, –40 et –60 kPa) et plusieurs niveaux de fertilisation ont été étudiés. Il a été établi qu'aux seuils de –40 et –60 kPa, les plantes ne parvenaient pas à compenser les déficits hydriques dans les conditions étudiées, en raison

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de sécheresses atmosphériques fréquentes. Les rendements les plus élevés ont été obtenus avec un seuil de déclenchement de -20 kPa. Concernant la fertilisation, après une application avant semis de N55,5P25,5K25,5 kg/ha de substances actives, les traitements comprenaient l'absence d'apport supplémentaire et une fertigation complémentaire de N80,5P0K44,2, N128,3P1,8K90,2 et N202,9P18,9K161,9 kg/ha de substances actives. Les rendements sont passés de 9,42 t/ha sans fertilisation supplémentaire à 11,24 t/ha avec l'apport maximal, avec un coefficient de corrélation de 0,79 entre le rendement et la quantité appliquée par fertigation. Nos résultats confirment la grande efficacité de l'irrigation goutte à goutte et la possibilité d'utiliser le potentiel capillaire pour déterminer les doses et les calendriers d'irrigation dans les conditions étudiées. Toutefois, lorsque les sécheresses atmosphériques sont fréquentes, l'irrigation goutte à goutte ne peut pas maintenir, sur les sols argileux, l'évapotranspiration nécessaire pour atteindre le potentiel de rendement des hybrides, principalement en raison de l'impossibilité de créer un microclimat atmosphérique favorable près de la surface, ce qui réduit également l'efficacité d'utilisation des éléments nutritifs.

Mots clés: Irrigation goutte à goutte; Fertigation, Maïs; Sols argileux; Ukraine.

INTRODUCTION

Under climate change, a significant increase in total evapotranspiration caused by an increase in the average annual temperature along with unchanged or even lower precipitation, has led to the emergence and progressive development of the process of aridification of the territory of Ukraine (Romashchenko et al., 2025b). As a result, there is a strong need to apply irrigation to achieve maximum productivity of crops as a mandatory and practically determining element of cultivation technologies.

In view of this, in 2023-2025 a set of studies was performed aimed at determining the conditions and effectiveness of using surface and subsurface drip irrigation to ensure maximum productivity of corn hybrids in the conditions of northern steppe of Ukraine on heavy-textured soils. The following results were obtained when studying the influence of different surface and subsurface drip irrigation regimes, as well as fertilization regimes, on the yield of two corn hybrids.

CLIMATIC CONDITIONS

The climate of the research area (Dnipropetrovsk region of Ukraine, Fig. 1) before the onset of the so-called "hot phase" of climate change since the late 1980s (Romashchenko et al., 2025b) was characterized as temperate continental with generally favorable conditions for growing most major crops. The average monthly air temperature varied in the range from -6.2 (January) to $+18.8$ °C (July), and the sum of active temperatures above 10 °C was from 2700 to 3400. Duration of the vegetation period was ~ 185 days.

Maximal amount of precipitation fell in summer, mainly in form of showers. The average annual precipitation was 550 mm in the northeast of the Dnipropetrovsk region and decreased in the southwest direction. The wettest month was July, the driest – March.

In summer, the amount of precipitation is 80% of the total annual amount. Relative humidity in July decreased in the southeast direction from 66% to 62%, in January it was 84 – 81%. The region is characterized by dry periods in spring and the first half of summer, intensified by dry winds. In the summer, western and north-western winds prevailed, in winter – eastern and north-eastern winds.

SOIL CONDITIONS

To characterize the specific soil conditions of the experimental site, a survey was initially conducted on 05.05.2023. The soil cover of the site is represented by ordinary low-humus light clay chernozem on loess-like loam. In the sub-sites, where surface (Section 1) and subsurface (Section 2) irrigation experiments were conducted, soil differs in the thickness of its layers. The structure of the soil consists

of humus (H0 – 40 [Section 1](53 [Section 2]) cm), upper transitional (Hp40(53) - 56(65) cm), lower transitional (Ph/k56(65) - 64(85)cm) layers and soil-forming rock (P/k64(85) – 100 cm and deeper).

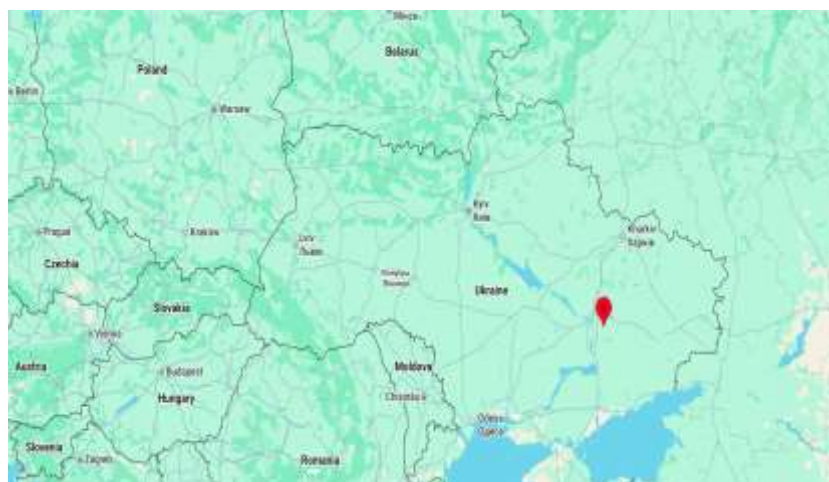


Figure 1. Location of the experimental site.

Source: <https://maps.google.com/?q=48.354053,35.582708&entry=gps>

In the humus-rich part, the soil has a Silty Clay texture, while in the soil-forming rock it has a Clay texture. In Section-1, the 0 - 70-90 cm soil layer has a physical clay content of 57.12 - 64.55%. Below this layer it is equal to 70.06 - 74.05%. In Section-2, the 0-90 cm soil layer has a clay content of 58.17 - 63.04%, which increases to 68.04% below.

The average soil density in the 0-30 cm layer is 1.24 - 1.26 g/cm³.

The hydro-physical properties of the soil, determined according to the procedure described in (Romashchenko et al., 2019), are presented in Table 1.

Table 1. Hydro-physical properties (ρ – final soil density; MH – maximum hygroscopicity (mass %); WP – withering point (mass %); SMC – volumetric saturated moisture content; FC – volumetric field capacity; AMR – volumetric active moisture content range)

Sample No.	Interval, m	ρ , g/cm ³	MH, %	WP, %	SMC, %	FC, %	AMR, %
Section 1							
27	0.10-0.25	1.45	9.54	12.78	50.71	42.58	32.13
40	0.30-0.45	1.43	9.86	13.21	50.38	41.69	31.49
23	0.60-0.75	1.49	9.91	13.28	47.22	37.27	27.49
Section 2							
25	0.12-0.27	1.45	9.71	13.01	54.70	45.79	35.76
36	0.30-0.45	1.33	10.17	13.63	54.03	40.19	35.91
20	0.55-0.70	1.49	9.36	12.54	48.72	37.38	30.06

In addition, water retention curves and hydraulic conductivity dependencies on the capillary potential were obtained in laboratory conditions. The values of the parameters of van Genuchten (van Genuchten, 1980) and Averianov (Averianov, 1982) models were then fitted to the experimental data (Table 2 for wetting curves).

Calculated by the kinetics of desorption, the FC values for both Sections correspond to high values of pressure (-1 – -4 kPa), i.e. in the case where the structural macropores are drained. At the same time, AMR, suitable for controlling the water regime by irrigation in the range from -40 – -60 kPa to FC, is significantly narrowed to 3.68 – 5.23%.

Regarding hydraulic conductivity, in general, its range changes with desorption by more than 1000 times. The nature of the profile variability of hydraulic conductivity in Section 1 is typical for old-arable soils, while in Section 2, the opposite picture is observed: for the arable layer, hydraulic conductivity values are minimal and increase with depth. Such variability is typical for uncultivated soils, or after a prolonged use of no-till technologies.

The level of provision with basic nutrients obtained in 2023 was lower than optimal; therefore fertilization was needed. A detailed agrochemical examination of the soil within the plant rows showed that the provision of soil with easily hydrolyzed nitrogen in the 0-30 cm layer was very low (91.0 - 98.0 mg/kg of soil) or low (100.8 – 112.0 mg/kg of soil). Similar data were obtained before sowing also in 2025.

Comparison of the results obtained in 2023 and 2024 showed that under the influence of irrigation and fertilization, the content of N increased from 104 to 154 mg/kg (from low to medium), P₂O₅ – from 64 to 108 mg/kg (from medium to high), K₂O – remained at an already elevated level. Such features of changes in the content of mobile forms of nutrients may also indicate amplification in biological processes in the soil under irrigation and acceleration of organic matter mineralization.

Table 2. Parameter values of van Genuchten and Averianov models (θ_r – residual moisture content; θ_s – saturated moisture content; n – shape parameter of van Genuchten model; a – the inverse of the air entry suction; k_r – hydraulic conductivity of saturated soil; β – the exponent in the Averianov model)

Sample No.	θ_r	θ_s	a, cm^{-1}	n	$k_r, \text{cm/day}$	β
27	0.3071	0.5071	0.07	1.25	15.552	4
40	0.2838	0.5038	0.07	1.25	4.32	2.7
23	0.2422	0.4722	0.07	1.25	9.504	3.7
25	0.287	0.547	0.1	1.2	8.64	3
36	0.2803	0.5403	0.07	1.3	31.104	3.5
20	0.2472	0.4872	0.09	1.27	259.2	6.55

SIMULATION OF WETTED ZONES

Using the obtained formalizations of soil's hydro-physical properties, in order to increase the accuracy of determination of irrigation rates and schedules, simulation of wetted zones was carried out according to the technique described in detail in (Romashchenko et al., 2025a). Moisture transport was modeled according to Richards equation in a two-dimensional approximation stated in terms of pressure. When conducting simulations, initial moisture distribution was taken equal to FC, after which soil drying was modeled until the average moisture content in the specified zone (40x30 cm around the emitter) did not become less than the pre-irrigation threshold. Then, the supply of irrigation water with a given flow rate was modeled until the average moisture content increased to the level of FC.

The simulation modeled an irrigation pipeline with a distance between emitters equal to 0.33 m, the flow rate of 1.2 dm³/h, and an installation depth of 0.25 m for the subsoil variant. Pre-irrigation thresholds were equal to -20, -40, and -60 kPa.

The simulation set-up was based on the previous results for the averaged hydro-physical properties of clay soils of Ukraine given in (Romashchenko et al., 2025a), according to which the maximum wetting zone is formed at the pre-irrigation threshold corresponding to 90% of FC and the installation depth of 0.30 m.

The results obtained placing the pipeline between plant rows showed the impossibility of ensuring the closure of wetted zones on the studied soil (Fig. 2a). In the case of placement in a row of plants (Fig. 2b), the simulated irrigation time varied from 1.28 h (surface irrigation, pre-irrigation threshold: -

20 kPa) to 1.76 h (subsurface irrigation, pre-irrigation threshold: -60 kPa). The corresponding irrigation rates varied from 66 m³/ha to 91 m³/ha.

EXPERIMENTAL DESIGN

Taking into account soil's hydro-physical properties and wetted zones simulations, it was determined that the system of both surface and subsurface drip irrigation should ensure the placement of irrigation pipelines in each row of crops (here with a distance of 70 cm). The depth of irrigation pipelines installation for subsurface drip irrigation should be 30 cm.

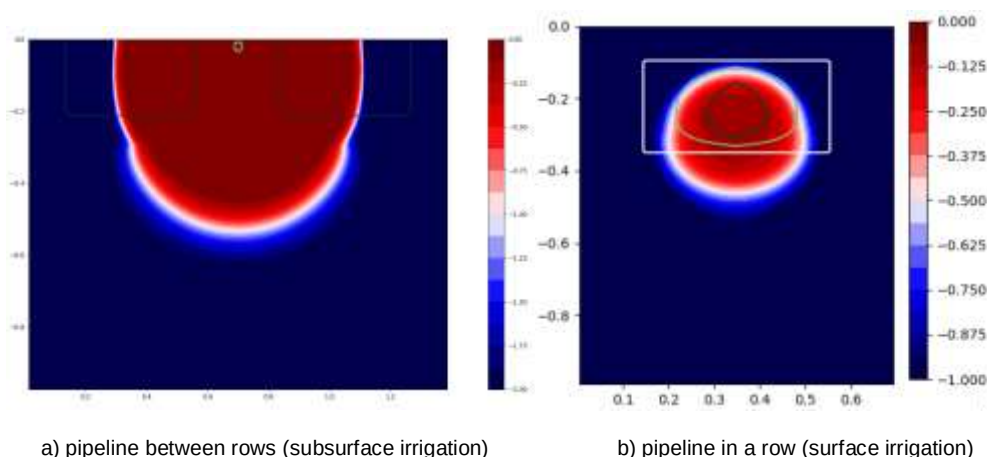


Figure 2. Simulated wetted zones immediately after the irrigation event (pre-irrigation threshold: -20 kPa)

The initial experiment in 2023 was designed without considering the above-mentioned facts and the pipelines were placed between rows assuming of the possibility of wetted zones closure. However, the simulations showed that it is impossible, which was also confirmed experimentally in 2023.

In 2024, the study was performed placing pipelines in the rows of plants. The influence of different irrigation regimes on the productivity of two hybrids (DMS Honor [FAO 340] and DMS Forsage [FAO 320]) was studied. Three irrigation regimes were studied for each of the two drip irrigation methods: -20 kPa÷FC; -40 kPa÷FC; -60 kPa÷FC. Each experimental variant contained three repetitions, and three control variants were set up.

The experimental design in 2025 included studying the effectiveness of drip irrigation at pre-irrigation thresholds of -20 kPa and -40 kPa with different rates of fertilizer application with irrigation water (background application for all options – N55.5P25.5K25.5 kg/ha of dry matter before sowing): only background application; background + N1.8P1.8K7.0 kg/ha; background + N80.5P0K44.2 kg/ha (“minimum”); background + N128.3P1.8K90.2 kg/ha (“average”); background + N202.9P18.9K161.9 kg/ha (“maximum”).

An iMetos weather station was installed on the experimental site with at least 2 Watermark sensors on each experimental variant, located at depths of 20 and 40 cm. Based on the monitoring data, the recommendations for irrigation were generated daily with a 5-day forecast using the “Polyv-Online” system (Bohaienko et al., 2021).

METEOROLOGICAL CONDITIONS AND MOISTURE SUPPLY

Conditions typical for an acutely dry year were observed at the experimental site in 2024. Almost 60% of the seasonal precipitation fell within one event. The weather station recorded atmospheric droughts that lasted 43 days.

In 2025, there was a smaller deficit in moisture supply with less rainfall than in 2024. Total evapotranspiration for the period from 15.06 to 7.09 amounted, according to calculations using various methods, from 503 to 603 mm, which is ~10% less than the values obtained in 2024 (from 626 to 668 mm). Atmospheric droughts lasted 37 days (Fig. 3). The total precipitation recorded during this period was 84 mm, with 44 mm that fell within two events. The weather conditions in 2025 are typical for a dry year.

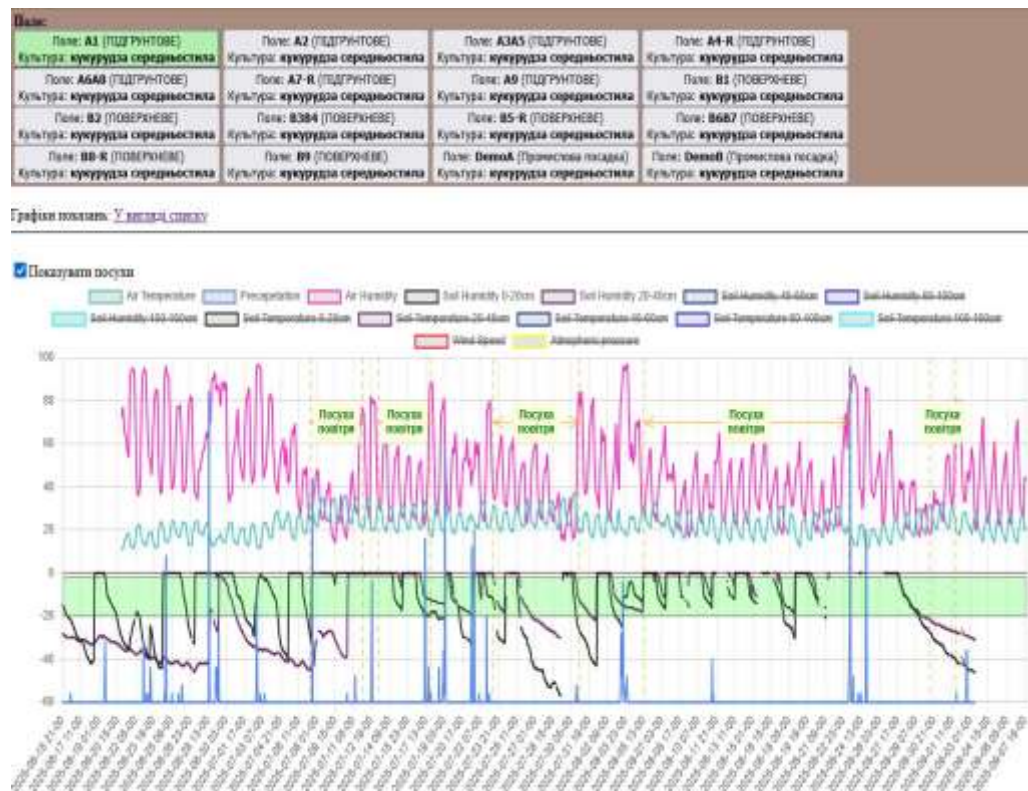


Figure 3. Dynamics of meteorological parameters and soil moisture suction pressure during subsurface drip irrigation (pre-irrigation threshold: -20 kPa; without additional nutrient supply; "Polyv-Online" system). Author: Smirnov A.M.

MOISTURE CONSUMPTION ANALYSIS

Given the long periods of atmospheric drought, it was assumed that the actual evapotranspiration during them was less than the potential one, which ultimately affected the yield. To confirm or refute this assumption, an analysis of indicators related to irrigation and moisture consumption by plants was conducted. The estimate of actual daily evapotranspiration ET, mm/day, from 50 cm layer was calculated as follows:

$$ET = -1000 \left(0.3(\theta_{20/40}^{(2)} - \theta_{20/40}^{(1)}) + 0.2(\theta_{40/40}^{(2)} - \theta_{40/40}^{(1)}) \right) + \sum_{i=0}^{24} (h_{40}^{(i)} - h_{20}^{(i)}) k_i / 0.2$$

where $\theta_{20/40}^{(2)}, \theta_{20/40}^{(1)}$, %, are soil moistures at the end and beginning of the day, calculated through the water retention curves according to the readings of sensors at depths of 20/40 cm; $h_{20/40}^{(i)}$, m, are water heads at the i-th hour of the day according to the readings of sensors at depths of 20/40 cm; k_i , mm/h, is the hydraulic conductivity in the i-th hour according to the readings of the sensor at the depth of 40 cm.

The example of calculated values according to 2024 data is shown in Fig. 4 for the pre-irrigation threshold of -20 kPa and surface irrigation.

Overall, the data collected in 2024 and 2025 show that the actual ET on days, when there was no irrigation, is close to the potential ET, determined by the weather station using the Penman-Monteith formula, only for the pre-irrigation threshold of -20 kPa.

For the data collected in 2025, a higher correlation coefficient ($R=0.58$) between potential and calculated ET was obtained for the pre-irrigation threshold of -20 kPa for surface irrigation compared to the value of $R=0.23$ for the pre-irrigation threshold of -40 kPa. Correlation coefficient values lower than 0.2 were expectedly obtained for the subsurface irrigation data, but even there, for the pre-irrigation threshold of -20 kPa, the calculated actual ET was closer to the potential one than in the case of -40 kPa.

In the absence of a significant correlation, a trend towards an increase in the estimated actual ET with the increase in relative air humidity was also recorded. This may be caused by the structural features of clay soils (low hydraulic conductivity), which, together with low air humidity (<40% on most days), creates conditions under which plants are unable to extract from the soil the amount of moisture necessary for their maximally productive development.

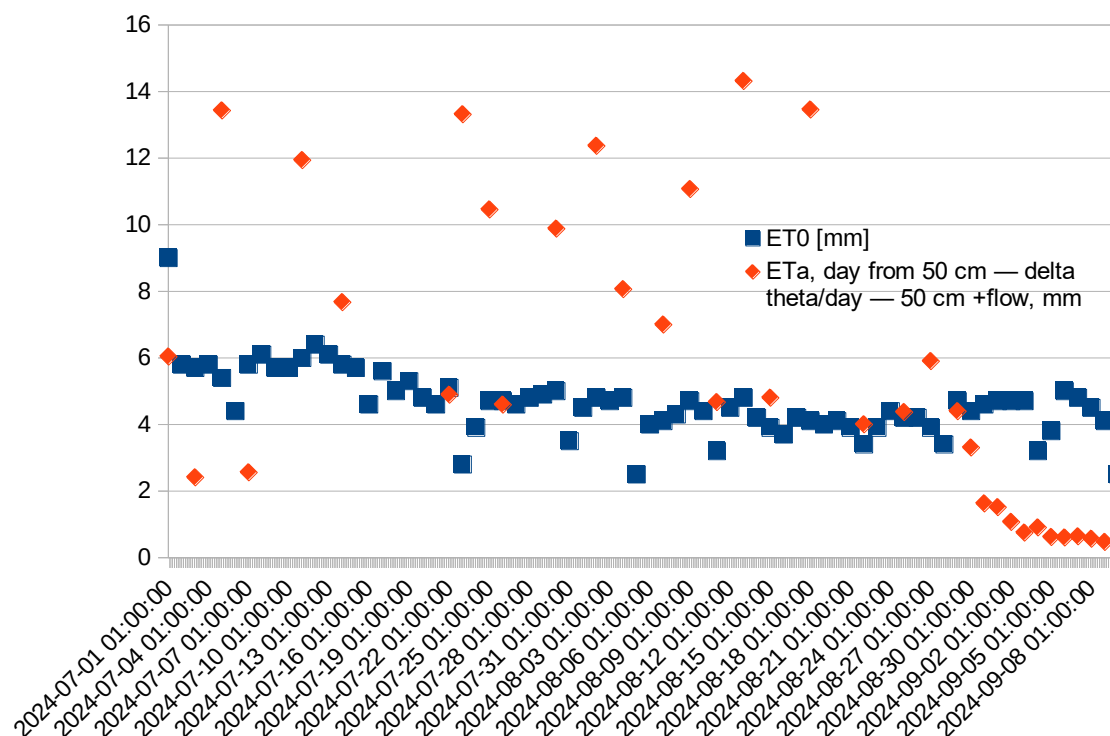


Figure 4. Potential evapotranspiration according to Penman-Monteith formula (ET0) and calculated actual evapotranspiration (ETa) for the 0-50 cm soil layer (pre-irrigation threshold: -20 kPa; surface irrigation).

As for the accuracy of actual irrigation, in 2024, at the pre-irrigation threshold of -20 kPa, high (>30%) coefficients of variation of actual pre-irrigation pressures were observed, confirming significant inaccuracies in implementing the irrigation schedule. At pre-irrigation thresholds of -40 and -60 kPa, the values of the coefficient was <25%.

In 2025 the average number of irrigation events for surface irrigation at the pre-irrigation threshold of -20 kPa was 21. In the case of subsurface irrigation, 32 irrigation events were performed. The average actual pre-irrigation threshold was -19.7 kPa with a coefficient of variation of 63%. Thus, the planned irrigation regime was carried out on average in accordance with the specified pre-irrigation threshold, however, with significant errors in the implementation of specific irrigation events. In the case of the

pre-irrigation threshold of -40 kPa, an average of 16 irrigation events was performed for surface irrigation and 30 - for subsurface irrigation. The average actual pre-irrigation threshold was -35 kPa with a coefficient of variation of 56%.

In 2025, actual irrigation events did not compensate for the loss of available soil moisture during the air droughts in June-July, which is a consequence of the human factor: improper implementation of irrigation schedule. Comparing to the untimely irrigation in June-July, during a prolonged air drought in August the irrigation regime was adjusted and pressures were maintained in a range even narrower than the specified one. In this case, an attempt to reduce the negative impact of air drought led to the implementation of an irrigation regime with a higher than planned average pre-irrigation threshold.

It should also be noted that after irrigation events, the soil was in a state close to saturated for a long time. The reason for this is the low hydraulic conductivity, and the consequence may be aeration stress of plants and a decrease in their yield. The threat of aeration stress is additionally exacerbated by the low level of water consumption of plants at the beginning of their vegetation.

CORN GRAIN YIELD

In 2024, without irrigation and fertilization, the average corn grain yield was 1.63 t/ha (1.17 – 2.04 t/ha across replications). Fertilization contributed to yield increase by ~10% or only 0.17 t/ha.

Clearly higher productivity of DMC Forsage hybrid was observed: without fertilization its yield exceeded the yield of DMC Honor hybrid by 0.72 t/ha (57%), with fertilization - by 0.9 t/ha (67%).

Irrigation contributed to a significant increase in corn grain yield. Under the surface variant, the yield increased by 3.8 times, and under the subsurface one - by 4.1 times that is 0.68 t/ha (10%) more than for the surface variant.

Regarding irrigation regimes, for surface drip irrigation, the option with the pre-irrigation threshold of -0.2 kPa was the best. The average yield here was 6.9-7.9 t/ha with a maximum of 8.6 t/ha. It was 10% higher than in the case of the pre-irrigation threshold of -0.4 kPa and 19% higher than in the case of -0.6 kPa. A similar tendency was observed for the subsurface variant.

One of the features of subsurface drip irrigation in 2024 was the close efficiency of irrigation regimes with pre-irrigation thresholds of -0.2 KPa and -0.4 KPa. This indicates a more efficient use of irrigation water with subsurface drip irrigation due to reduced losses to physical evaporation.

In 2025, without irrigation and without fertilizing during the growing season, the yield averaged 1.84 t/ha (from 1.15 to 2.81 t/ha), which is 0.21 t/ha more than in 2024. Foliar fertilization with micronutrients without irrigation, unlike in 2024, did not contribute to a significant increase in the yield of both hybrids.

In 2025, similarly to 2024, the DMC Forsage hybrid was more productive, its yield exceeded the DMC Honor hybrid by 35-38%.

Irrigation, on average across all experiment variants, contributed to an increase in corn grain yield to almost 10.0 t/ha. Surface irrigation was more effective in 2025 with yields 4% higher than in the case of subsurface irrigation.

At the pre-irrigation threshold of -40 kPa, the yield ranged from 8.99 to 10.0 t/ha. At -20 kPa it was 4% higher.

The yield under surface irrigation at the pre-irrigation threshold of -20 kPa was ~0.53 t/ha or 5% higher than at -40 kPa. Under subsurface drip irrigation, the difference was ~0.32 t/ha or 3%. The results of 2025 confirm the conclusion that the subsurface drip irrigation method is more plastic to irrigation regimes under the studied conditions.

To study the effect of different rates of mineral fertilizers on the yield of corn hybrids, their productivity was compared to the variant with only a background application of fertilizers before sowing. Averaged among different fertilization rates, the yield was 9.97 t/ha, which is 0.85 t/ha or 9% higher than in the variant with only background application.

When fertilizers were applied during the growing season, the surface irrigation was more effective with 13% yield increase compared to 6% for subsurface variant. The effectiveness of “minimum” and “average” fertilization options was close. Under the “maximum” regime, the yield was ~10.46 t/ha, which is 1.34 t/ha or 15% higher than in the control variant. With surface irrigation, the difference increased to 1.67 c/ha. The correlation coefficient between yield and the amount of additional fertilizer application is 0.79.

CONCLUSIONS

1. The efficiency of irrigation in growing corn under the studied conditions has been confirmed - the yield is up to 5.3 times higher compared to conditions without irrigation.
2. The results confirmed the efficiency of using water retention curves and the capillary potential of the soil to determine the optimal range of moisture supply. Even in conditions of clay soils with an extremely limited range of easily available moisture (0.9 FC÷FC), it was possible to avoid irrigation regimes with pre-irrigation thresholds outside this range.
3. A decrease in actual evapotranspiration during the periods of atmospheric drought, which affects the yield, was recorded. This confirms the statement that in conditions of an atmospheric drought, drip irrigation is unable to ensure the actual water consumption of corn plants maintained at the potentially possible level, and therefore the maximum level of yield is not obtained. In particular, the reason for this is the impossibility of forming a favorable microclimate in the surface layer of air, which reduces not only actual water consumption, but also efficiency of nutrients use by plants.
4. The irrigation of corn on heavy-textured soils with a narrow range of moisture available to plants and weather conditions with low air humidity requires the application of irrigation regimes that do not allow the average value of suction pressure in root-containing zones to decrease below -20 kPa, since under other conditions, corn plants are not able to extract the amount of moisture from the soil necessary for their effective development.
5. The highest yields of both studied corn hybrids under both irrigation methods were obtained under the irrigation regime with maintaining the level of moisture supply of the root layer of the soil in the range -20 kPa÷FC and at the maximum level of mineral nutrition at the level of N258.4P44.4K187.4 kg/ha, including fertilization by fertigation at the level of N202.9P18.9K161.9 kg/ha.

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