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## RESEARCH ARTICLE

# Assessment of the Impact of Deficit Irrigation on Grapevines in the Semi-Arid Region of Ukraine Using the AquaCrop Model

AquaCrop Modeli Kullanılarak Ukrayna'nın Yarı Kurak Bölgesinde Kısıtlı Sulamanın Asma Üzerindeki Etkisinin Değerlendirilmesi

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### ABSTRACT

This study aimed to evaluate the effectiveness of deficit irrigation for wine grape varieties in the semi-arid region of Ukraine using the AquaCrop model. Developed by the FAO, AquaCrop simulates crop productivity based on the soil-plant-atmosphere water balance. The modeling considered agrometeorological conditions during the growing season, including canopy cover, transpiration activity, soil moisture dynamics, biomass accumulation, water balance, yield, and water productivity. The results demonstrated that moisture deficiency during leaf area formation was the main limiting factor for productivity. A significant slowdown in canopy expansion (40 %) led to reduced seasonal transpiration and a 14 % decrease in biomass. In contrast, limitations in gas exchange due to stomatal closure were minor (7 %), while heat stress effects were negligible (4 %), playing only a minor role in the overall productivity balance. The simulated yield reached 10.7 t/ha, confirming the stability of yield formation mechanisms even under hydrothermal instability. To ensure full leaf area development and enhance vineyard productivity, irrigation management should be optimized with an emphasis on the early stages of grapevine growth.

### MAKALE BİLGİSİ

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### ÖZ

Bu çalışma, Ukrayna'nın yarı kurak bölgesinde şaraplık üzüm çeşitleri için kısıtlı sulamanın etkinliğini AquaCrop modeli kullanarak değerlendirmeyi amaçlamaktadır. FAO tarafından geliştirilen AquaCrop, bitki verimliliğini toprak-bitki-atmosfer su dengesi temelinde simüle etmektedir. Modelleme sürecinde, büyüme dönemi boyunca agroklimatik koşullar; yaprak alanı örtüsü, transpirasyon aktivitesi, toprak nemi dinamikleri, biyokütle birikimi, su dengesi, verim ve su verimliliği dikkate alınmıştır. Sonuçlar, yaprak alanı oluşumu sırasında ortaya çıkan nem yetersizliğinin verimlilik için temel sınırlayıcı faktör olduğunu göstermiştir. Yaprak örtüsünün gelişimindeki %40'luk yavaşlama, mevsimlik transpirasyonun azalmasına ve biyokütlede %14'lük kayba neden olmuştur. Buna karşılık, stoma kapanmasına bağlı gaz değişimi kısıtlamaları (%7) ve sıcaklık stresinin etkileri (%4) oldukça düşük bulunmuş ve toplam verimlilik dengesinde önemsiz rol oynamıştır. Simülasyon sonuçlarına göre verim 10,7 t/ha olarak belirlenmiş ve hidrotermal dalgalanmalara rağmen verim oluşum mekanizmalarının istikrarı doğrulanmıştır. Yaprak yüzeyinin tam gelişimini sağlamak ve bağların toplam verimliliğini artırmak için sulama yönetiminin özellikle vegetasyonun erken dönemlerinde optimize edilmesi önerilmektedir.

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## Introduction

Periodic droughts and dry winds in Ukraine's semi-arid regions cause significant losses in agricultural production (Vozhegova, 2019). Irrigation is therefore a key adaptation measure, ensuring stabilization of crop water regimes under such conditions (Romashchenko, 2013). However, determining scientifically sound irrigation schedules remains an urgent task for the effective implementation of land reclamation technologies. These schedules must consider soil and climatic conditions, cultivation practices, and economic criteria related to yield and product quality (Kaletnik, 2014).

In semi-arid zones where surface water resources are scarce, vineyards are frequently irrigated using water pumped from deep aquifers (100–120 m) (Vozhegova et al., 2014). Yet, the limited capacity of artesian wells, combined with the high energy costs of pumping and the risk of groundwater depletion, makes this method unsuitable for large-scale production. These challenges highlight the relevance of deficit irrigation, a management strategy that optimizes irrigation timing and volume to ensure more efficient use of water resources (Munitz et al., 2017; Bonada et al., 2023). This approach allows growers to sustain crop productivity and maintain grape quality even under restricted water availability (Torres et al., 2021).

With increasing aridification driven by global climate change, enhancing the efficiency of irrigation water use has become a critical factor for sustainable viticulture (Flexas et al., 2010). In this context, developing physiological principles that improve grapevine productivity and optimize water use under moisture-limited conditions is of particular importance (Tomás, 2014).

Numerous studies on field crops have demonstrated the effectiveness of the AquaCrop model for designing and scientifically substantiating irrigation strategies (Steduto et al., 2009). Developed by the FAO, AquaCrop evaluates the effects of water regimes on crop yields under water-limited conditions, making it highly relevant for arid and irrigated environments. The model integrates climatic parameters, soil physical and chemical properties, crop-specific biological traits, and cultivation practices. This enables the simulation of the impacts of water deficit and climate variability on crop productivity (Steduto et al., 2012).

Previous applications of AquaCrop have shown high efficiency in planning irrigation for table grape production in the arid climate of northwestern Mexico (Er-Raki et al., 2021). However, its use for wine grape varieties—particularly in the context of deficit irrigation strategies—remains insufficiently studied, underscoring the need for further research. Unlike table grapes, where yield and berry size are the primary objectives, wine grape cultivation prioritizes the balance between vegetative growth and the accumulation of quality-related metabolites. Consequently, the physiological sensitivity of wine grape varieties to water stress requires a more nuanced modeling approach to accurately predict crop responses under deficit irrigation conditions.

The objective of this study was to optimize deficit irrigation strategies for wine grape varieties in the semi-arid region of Ukraine using the AquaCrop model, thereby providing a scientific basis for sustainable water management and enhanced viticultural productivity under regional soil and climatic conditions.

## Materials and Methods

### Research Site

The study was carried out in the Borodino community, Odesa region, Ukraine. According to long-term agrometeorological records, the area has a cold semi-arid climate, with a mean annual temperature of 10.5 °C. Winter temperatures occasionally fall to –20 °C, reaching as low as –24 °C once per decade, while summer temperatures regularly exceed 35 °C. Annual precipitation averages 482 mm, of which 316 mm occur during the growing season.

The experimental site covered 0.55 ha and was planted with the autochthonous wine grape variety Odeskyi Chorny (46°29' N, 29°41' E). Vines were spaced 0.9 m within rows and 2.1 m between rows, trained to a cordon system on a 1.8 m single-plane vertical trellis. The soil was classified as heavy loam Chernozem, consisting of 54 % physical clay (< 0.01 mm) and 14 % silt (< 0.001 mm).

Irrigation was applied using a drip system with pipelines and emitters (0.9 L h<sup>-1</sup>) installed 0.6 m above the soil surface along the trellis rows. A deficit irrigation strategy was implemented, supplying water during

the growing season when crop evapotranspiration (ET<sub>c</sub>) reached 50 % of crop water requirements. This approach accounted for limited water resources under arid conditions. Previous studies have confirmed that maintaining irrigation at 50 % ET<sub>c</sub> represents a moderate water stress strategy for wine grapes, based on a deliberate restriction of water supply (Wang et al., 2019; Losciale et al., 2024).

### Equipment and Measurement Methods

The impact of deficit irrigation on grapevine productivity was evaluated using the AquaCrop model (version 7.1). This model, developed by the FAO Land and Water Division, simulates crop yields based on the water balance of the soil–plant–atmosphere continuum (Raes et al., 2023).

According to official methodological recommendations (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009), simulation of the production process requires a structured set of input data, organized into four principal categories:

Climate: meteorological variables including temperature, precipitation, evaporation, and solar radiation.

Crop: biological and phenological parameters of crop growth and development.

Management: agronomic practices, particularly irrigation scheduling.

Soil: physical and hydrological properties of the soil profile.

### Creation of the "Climate" Data Block

The climate dataset was compiled from agrometeorological observations during the 2024 grape-growing season, covering the period from bud break to harvest. Daily measurements included precipitation, reference evapotranspiration (ET<sub>o</sub>), and maximum, minimum, and mean air temperature.

Primary meteorological data were obtained using an Inspector Meteo™ (IT-Lynx™) automatic weather station equipped with certified sensors. The collected data were processed with an integrated calculator that computes ET<sub>o</sub> values in accordance with FAO guidelines, thereby ensuring compliance with AquaCrop input requirements.

### Creation of the "Crop" Data Block

Because grapevine is not included in the standard AquaCrop database, a separate crop file was developed following the procedure used for perennial fruit crops. The principal biological difference between grapevine and annual crops lies in the onset of the growing season, which for grapevine begins with bud break rather than sowing. Subsequent phenological phases, however, are sufficiently similar to those of other crops to allow correct model adaptation.

The “Crop” block was established using field observations of grapevine growth and development during the 2024 growing season. The input parameters of the AquaCrop model, adapted for the Odeskyi Chorny wine grape variety, are presented in Table 1.

**Table 1.** Input parameters of the AquaCrop model for grapevine and their interpretation.

Parameter	Unit	Value	Comment
Initial canopy cover (CC <sub>0</sub> )	%	5.1	Typical for grapevines on trellises at the onset of the growing season.
Time to CC <sub>0</sub>	days	29	Vegetation began on April 8, 15 days earlier than average; however, the initial development phase was prolonged.
Maximum canopy cover (CC <sub>x</sub> )	%	19	Corresponds to low leaf area coverage, characteristic of row crops.
Time to CC <sub>x</sub>	days	127	The period of intensive vegetative growth ended in July, after which active berry growth commenced.
Time to onset of leaf senescence	days	142	Partial senescence initiated during berry ripening in August.
Time to complete leaf	days	220	Complete senescence occurred after the first frosts in

Parameter	Unit	Value	Comment
senescence			November.
Time to flowering	days	54	Flowering began in June and lasted approximately 14 days.
Time to harvest	days	180	Harvesting of the Odeskyi Chornyi variety commenced on October 4.
Root depth	m	1.00	About 80% of the root system in heavy loam chernozem soils was concentrated at a depth of 1 m.
Optimum temperature	°C	10–35	Within the known thresholds for <i>Vitis vinifera</i> L. growth and development.

In AquaCrop, canopy cover (CC) is a key parameter for estimating transpiration and soil evaporation, which in turn determine biomass accumulation and yield. From the perspective of radiation balance, CC reflects the ratio of leaf surface area to the ground area it covers. For trellised vineyards with regular row spacing, it is appropriate to use the horizontal projection of the canopy as the basis for calculation, in contrast to crops established by continuous sowing. In this case, CC is defined as the percentage ratio of a vine's horizontal canopy projection to its feeding area, adjusted for canopy gaps.

Biomass growth in grapevine is modeled analogously to other crops with C3 photosynthesis, assuming a mean water productivity of 17.0 g m<sup>-2</sup>. For grapevine, an acceptable harvest index of 50 % was used to estimate the economically valuable portion of the crop (berries). Conversion of biomass into fresh grape yield was performed using average compositional values typical of wine grapes: 30 % dry matter and 70 % water. These parameters ensured consistency of model outputs with actual productivity and quality indicators, which is essential for evaluating irrigation efficiency under conditions of water scarcity.

#### Creation of the "Management" Data Block

The "Management" block includes information on irrigation practices and soil conservation measures that influence the water balance and crop productivity. As noted earlier, the vineyard employed a deficit irrigation strategy at 50 % ET<sub>c</sub> in response to limited regional water resources.

During the 2024 growing season, five irrigation events were applied at an average depth of approximately 55 mm, maintaining the water balance at the prescribed level. The wetted soil area was estimated at about 10 %, based on the discharge rate of individual emitters (0.9 L h<sup>-1</sup>) and the total emitter density (5,291 ha<sup>-1</sup>). The irrigation water was of high quality, derived from deep artesian aquifers (>100 m).

To enhance water-use efficiency, the farm also implemented autumn and winter practices aimed at moisture conservation, including systematic tillage and bare-fallow management. The absence of vegetation cover, combined with regular soil loosening and aeration, improved infiltration, reduced compaction, and created favorable conditions for the accumulation of productive moisture.

#### Creation of the "Soil" Data Block

The "Soil" block was developed based on the physical and hydrological properties of soil samples collected from the experimental site (Table 2). Laboratory analysis showed that the upper layer (0–50 cm) was well structured, loose, and highly porous, conditions that favor active root development. By contrast, the lower layer (50–100 cm) exhibited higher bulk density, typical of poorly aerated horizons. The mean bulk density of the 0–100 cm profile was 1.26 g cm<sup>-3</sup>, which corresponds to optimal conditions for grapevine growth.

Soil water properties were characterized using three key indicators: saturation moisture content ( $\theta_{sat}$ ), field capacity ( $\theta_{FC}$ ), and wilting point moisture content ( $\theta_{WP}$ ). The total available water (TAW) in the 0–100 cm layer was 150 mm m<sup>-1</sup>, indicating a high potential for water storage, typical of fertile heavy loam soils.

Overall, the soil at the site provides favorable conditions for grapevine cultivation under moderate

water supply. However, supplemental irrigation is required during the summer dry period (July–August) to prevent water stress. While the soil has a high water-holding capacity, ensuring the accumulation of productive moisture reserves for most of the growing season, the elevated bulk density in the 50–100 cm horizon may restrict root penetration and limit water uptake from deeper layers.

**Table 2.** Physical and hydrological properties of soil samples (laboratory analysis).

Sampling depth, cm	Bulk density, g/cm <sup>3</sup>	Moisture content (m <sup>3</sup> /m <sup>3</sup> )			TAW 1000(θ <sub>FC</sub> - θ <sub>WP</sub> ), mm/m
		saturation (θ <sub>sat</sub> )	field capacity (θ <sub>FC</sub> )	wilting point (θ <sub>WP</sub> )	
0-50	1.19	0.54	0.31	0.14	170
50-100	1.34	0.49	0.30	0.16	140
0-100 (average)	1.26	0.51	0.30	0.15	150

\*Soil type: heavy loam chemozem. TAW – total available water.

### Simulation Modeling of Agrobiological Processes

Crop growth, water balance, and yield were simulated in AquaCrop using the specified input parameters together with actual soil moisture values measured at the onset of the growing season. During the bud break phase, soil moisture was determined by the thermostatic–weight method, and the results were entered into the corresponding model block. To evaluate the accuracy, reliability, and adequacy of the simulations, the following parameters were measured in the field throughout the growing season: canopy cover, dry biomass, and soil moisture content.

Comparison between simulated and observed data was performed using established statistical criteria of model performance: *r* – correlation coefficient, reflecting the linear relationship between simulated and observed values; RMSE – root mean square error, quantifying forecast accuracy; EF – model efficiency coefficient, indicating the overall predictive quality; *d* – index of agreement, assessing the degree of correspondence between simulated and empirical data.

## Results and Discussion

### Agrometeorological Conditions of the 2024 Growing Season

As shown in Figure 1, monitoring data revealed pronounced seasonal fluctuations in air temperature during the 2024 grape-growing season.

From days 1 to 54 (April–May), temperatures remained relatively low. Average minimum values were 7.3–7.5 °C, with occasional drops to 0.6–2.3 °C, indicating a risk of late spring frost. Average maximum temperatures reached 20.5–22.5 °C, creating favorable conditions for the onset of vegetative growth.

During days 55 to 84 (June), a marked increase in temperature was observed. The average minimum rose to 16 °C, while the average maximum reached 30.2 °C, with an absolute maximum of 34.4 °C. These conditions were optimal for shoot growth and flowering.

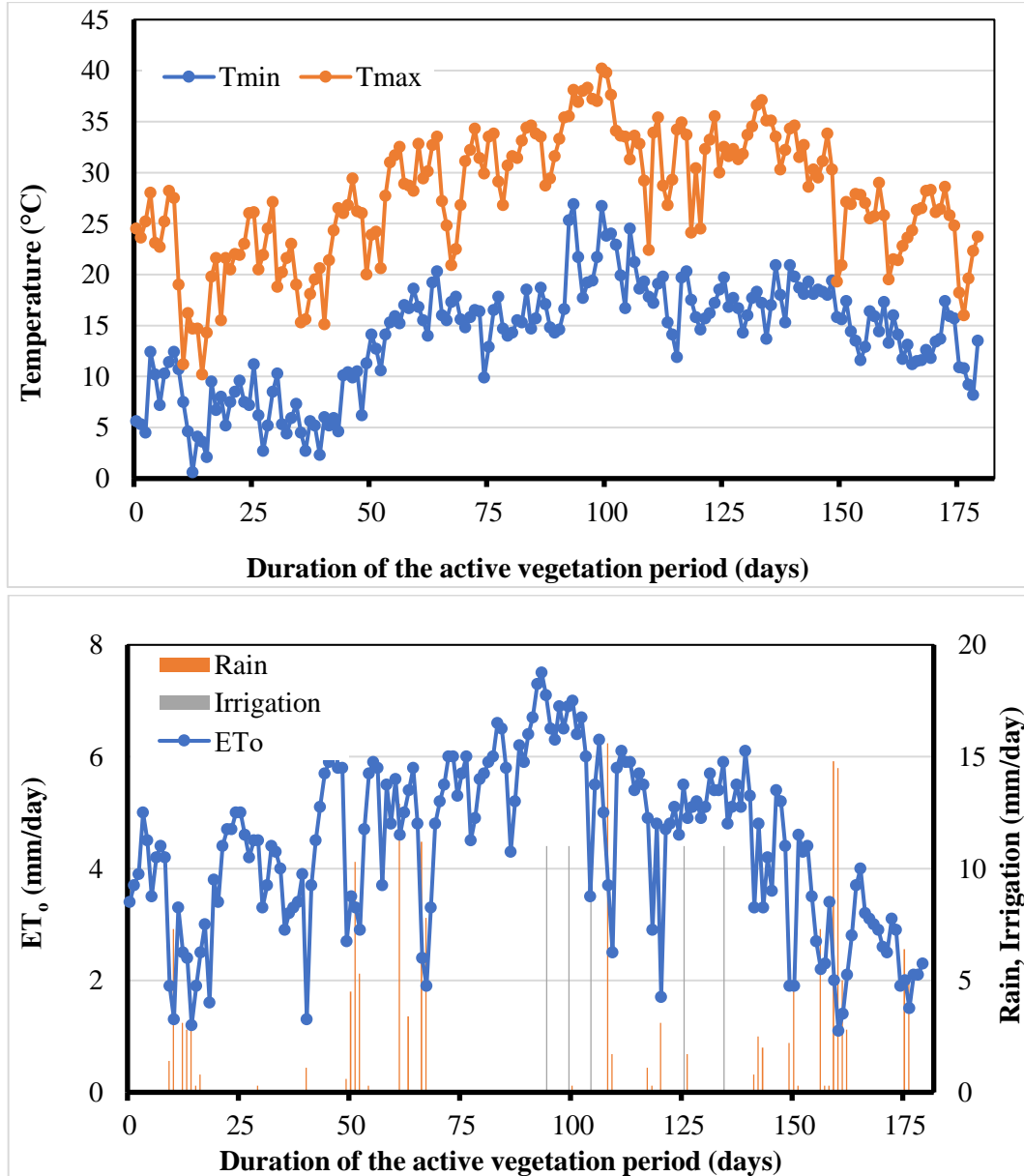
The warmest period occurred between days 85 and 146 (July–August). Average minimum temperatures ranged from 19.3 to 17.4 °C, while average maximums declined slightly from 33.7 to 32.3 °C. In July, the absolute maximum reached 40.2 °C, a level critical for grapevine physiology. Such extreme heat may induce stress, suppress photosynthesis, and increase the risk of berry sunburn.

From days 147 to 180 (September–October), temperatures gradually declined. Average minimums ranged from 14.5 to 10.4 °C, while average maximums ranged from 25.7 to 20.4 °C. Absolute minimum values of 8.2–10.8 °C indicated the end of active vegetation. These conditions were favorable for berry ripening and sugar accumulation.

Overall, thermal conditions during the season were within the biological requirements of grapevine, ensuring full crop development. However, risks such as late spring frosts (down to 0.6 °C in April) and extreme summer heat (up to 40.2 °C in July) may negatively affect physiological processes.

Analysis of reference evapotranspiration ( $ET_0$ ), precipitation, and irrigation volumes provided insight into the vineyard's water supply and revealed critical phases of water shortage.

In April,  $ET_0$  averaged  $3.2 \text{ mm day}^{-1}$ , while precipitation totaled  $19.6 \text{ mm}$ , fully meeting crop demand and leading to soil moisture accumulation. In May,  $ET_0$  increased to  $4.2 \text{ mm day}^{-1}$ , with  $22.1 \text{ mm}$  of precipitation maintaining a neutral water balance. In June,  $ET_0$  reached  $5.1 \text{ mm day}^{-1}$ , while precipitation amounted to  $35.6 \text{ mm}$ , preventing a water deficit.



**Figure 1.** Agrometeorological profile of the 2024 grape-growing season: daily dynamics of air temperature ( $T_{min}$ ,  $T_{max}$ ), reference evapotranspiration ( $ET_0$ ), and water supply (precipitation and irrigation).

July was the most critical month, with  $ET_0$  averaging  $5.9 \text{ mm day}^{-1}$  (maximum  $7.5 \text{ mm}$ ) and precipitation totaling only  $17.6 \text{ mm}$ . To mitigate the deficit,  $33 \text{ mm}$  of irrigation was applied. In August,  $ET_0$  remained high ( $4.8 \text{ mm day}^{-1}$ ), but precipitation was critically low ( $11.5 \text{ mm}$ ). Irrigation of  $22 \text{ mm}$  partially compensated for the shortage, though water stress persisted.

In September,  $ET_0$  declined to  $3.0 \text{ mm day}^{-1}$ , while precipitation reached  $58.9 \text{ mm}$ , fully covering crop requirements. In October,  $ET_0$  decreased further to  $2.0 \text{ mm day}^{-1}$ , with precipitation of only  $5 \text{ mm}$ . This was not limiting, as the growing season was ending.

In summary, water availability was generally favorable, except in July and August, when supplemental

irrigation (55 mm in total) was essential to maintain the water balance. The substantial precipitation in September created natural reserves that supported ripening and prevented additional stress.

### Canopy Cover and Transpiration Activity

The grapevine growing season commenced in April with bud break, when vegetative growth was minimal and foliage cover was nearly absent. From May to July, intensive leaf area expansion was observed, reaching a maximum canopy cover of 17 % in August. Thereafter, from September to October, canopy cover gradually declined, reflecting the onset of senescence. This restricted development is attributed to the high sensitivity of the canopy expansion stress coefficient ( $K_{s,exp}$ ) in the AquaCrop model to early-season soil moisture depletion. Such structural limitations at the beginning of the vegetative cycle reduce the total intercepted solar radiation, creating a cascading effect that limits potential transpiration and overall biomass accumulation. Furthermore, the stabilization of canopy cover at 17 % is influenced by the vertical trellis system and green operations, which physically restrict foliage expansion within defined spatial limits. These viticultural practices, in conjunction with early-season water stress, account for the 40 % slowdown in canopy development and effectively cap the crop's maximum transpiration capacity, as illustrated in Figure 2.

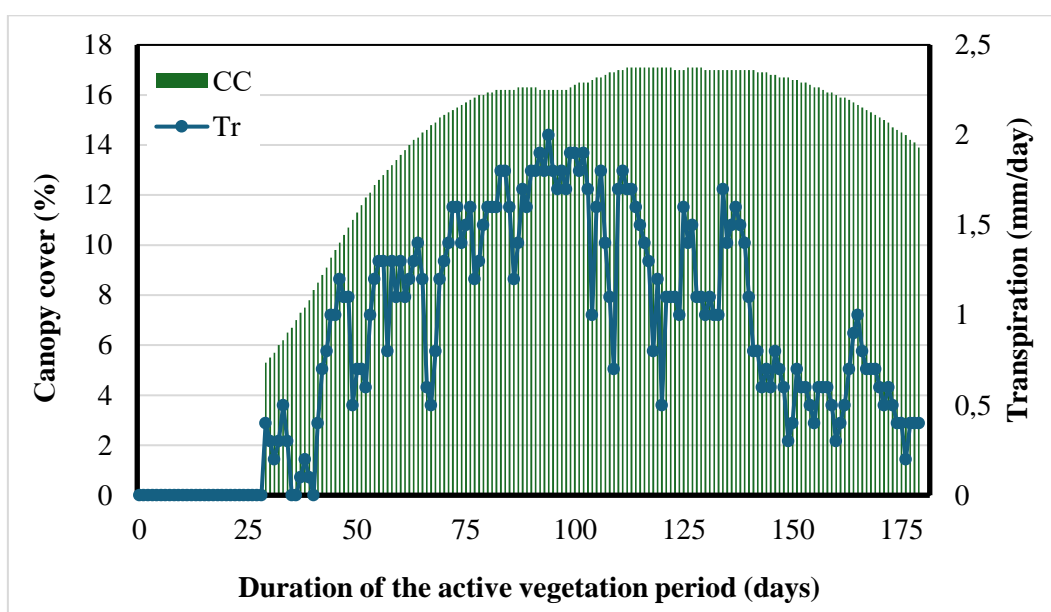


Figure 2. Seasonal dynamics of canopy cover (CC) and actual transpiration (Tr) of grapevine in 2024.

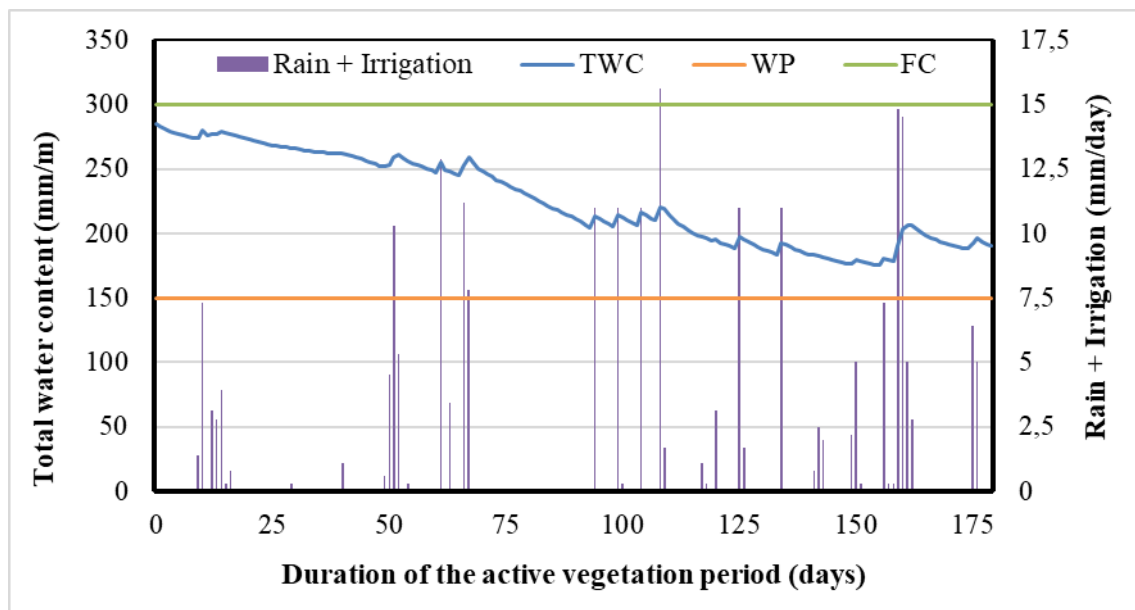
Transpiration dynamics closely followed canopy development. The highest transpiration activity was recorded in July, with an average of  $1.6 \text{ mm day}^{-1}$  and a maximum of  $2.0 \text{ mm day}^{-1}$ . In August, transpiration decreased, likely due to the onset of physiological leaf aging and/or changes in weather conditions. By October, transpiration stabilized at low levels consistent with the completion of the growing season.

The results demonstrate a strong correlation between leaf area development and transpiration intensity. This direct dependency is evidenced by the 40 % slowdown in canopy expansion (Fig. 2), which effectively capped the maximum transpiration rate by restricting the available leaf surface area for gas exchange. Consequently, the observed peak in water use was fundamentally constrained by the structural deficit established during the early growth stages. Leaf biomass accumulation was associated with increased water consumption, with the critical period of water demand occurring from June to August, during active growth and peak moisture use. Optimizing irrigation during this interval is therefore essential to maintain stable transpiration activity.

In midsummer (July), maintaining adequate soil moisture is critical for the effective functioning of the transpiration mechanism. Conversely, in autumn, as physiological activity declines, irrigation requirements can be gradually reduced.

### Soil Water Storage

The soil moisture modeling results (Figure 3) demonstrate pronounced seasonal dynamics during the 2024 grape-growing season. Beginning in April, average soil water content declined steadily, reaching minimum values of 188–189 mm in August–September, approaching the critical wilting threshold of 150 mm.



**Figure 3.** Simulated soil water dynamics in relation to total water content (TWC), field capacity (FC), and wilting point (WP).

The greatest precipitation inputs occurred in July (50.6 mm) and September (58.9 mm), which partially offset moisture losses caused by high transpiration demand. In October, precipitation decreased sharply (5 mm), but soil water storage increased slightly, most likely due to reduced crop water consumption at the final stage of vegetation.

From June to September, a pronounced water deficit was observed, with soil moisture consistently below the optimal level of 300 mm. This interval coincided with active biomass accumulation and crop formation, when grapevines have the highest water requirements. Under such conditions, effective irrigation management is essential to sustain transpiration and ensure stable growth.

September proved to be a particularly critical month for crop development, emphasizing the need to maintain a stable soil water regime. By contrast, in October, as crop water demand declined, soil water storage stabilized, thereby preventing additional stress.

### Grapevine Biomass Accumulation

Biomass accumulation in grapevine during the growing season was gradual yet consistent. From May to October, total biomass steadily increased, with the most intensive growth observed between June and August, when it rose from 1.296 to 4.455 t ha<sup>-1</sup>. This period corresponded with active shoot elongation, leaf area expansion, and the onset of generative development (Figure 4).

Yield formation began in June, when fruit biomass was only 0.076 t ha<sup>-1</sup>. The main phase of production accumulation occurred in July–August, when yield reached 2.028 t ha<sup>-1</sup>, representing 45.1% of total biomass. From September to October, yield growth slowed, while the harvest index (HI) stabilized at 50%.

As an integral indicator of productivity, HI increased from 3.4% in June to 50% in September, marking the completion of the plant's productive organs. The highest efficiency of biomass partitioning into yield was recorded in July–August, coinciding with peak physiological activity and water demand.

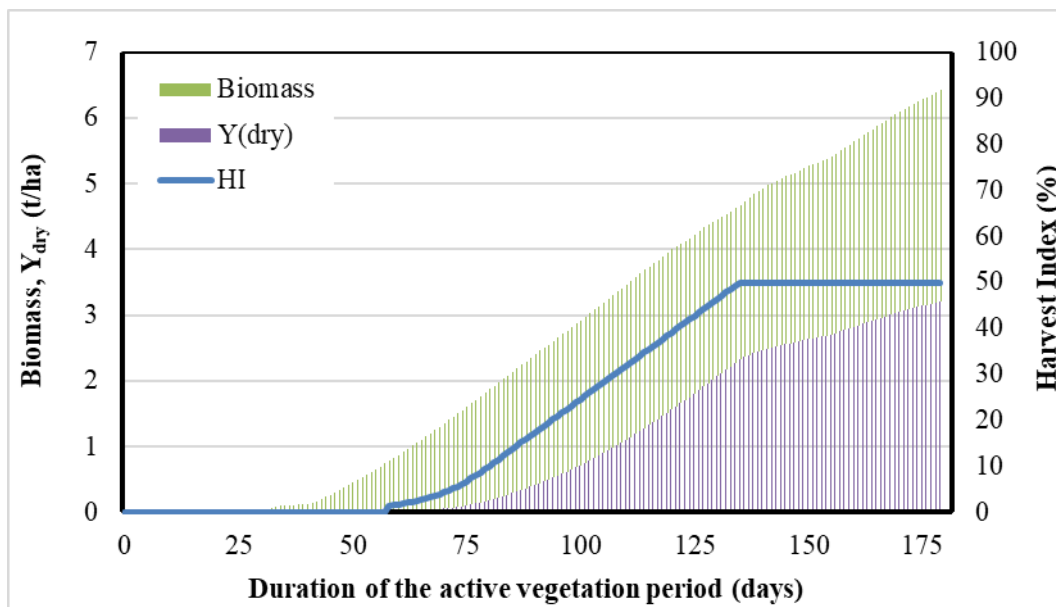


Figure 4. Seasonal dynamics of biomass accumulation and grapevine yield (Ydry) formation in 2024.

Stabilization of HI in September–October indicated the end of the productive cycle and the transition to ripening, when fruit quality attributes are formed. These results confirm the critical importance of maintaining optimal soil water availability during the active accumulation phase.

**Water Balance, Yield, and Crop Water Productivity**

The modeling results indicate that grapevine exhibits high water-use efficiency, with a crop water productivity of 1.00 kg m<sup>-3</sup>, consistent with optimal values for perennial crops under limited water availability. This level reflects the crop’s capacity to effectively convert available soil moisture into yield, even under deficit conditions (Table 3).

Actual evapotranspiration (ET) was only 42 % of the potential rate, yet yields remained stable. This suggests that the crop experienced a moderate water deficit that did not critically affect productivity. At the same time, actual transpiration (Tr) exceeded 90 % of its maximum, indicating that active physiological processes were preserved and that severe stress was avoided. The limited impact of stomatal closure suggests that soil moisture, while restrictive for expansion, remained above the severe depletion levels required to trigger gas-exchange inhibition. This physiological resilience is further supported by the high thermal adaptation of the selected wine grape variety to the semi-arid climate of the Northern Black Sea region, which effectively mitigated heat-induced stress.

Table 3. Summary of water balance, yield, and water use efficiency in grapevine.

Parameter	Unit	Value	Comment
Maximum crop transpiration (Trx)	mm	170.3	Potential under conditions of full water supply
Actual crop transpiration (Tr)	mm	157.2	92.3% of potential, indicating moderate deficit
Maximum evapotranspiration (ETx)	mm	763.4	Includes soil evaporation losses
Actual evapotranspiration (ET)	mm	320.9	42% of potential, reflecting water conservation or limited access to moisture
Dry yield (Y <sub>dry</sub> )	t ha <sup>-1</sup>	3.21	High productivity under limited water conditions
Water productivity (WP <sub>et</sub> )	kg m <sup>-3</sup>	1.00	Yield (kg) per cubic meter of water evapotranspired



According to AquaCrop simulations, water use remained balanced. Even with restricted moisture supply, high yields can be sustained provided that transpiration is maintained at sufficient levels. This underscores the effectiveness of adaptive irrigation strategies that prioritize transpiration activity—the key driver of productive water use—over the pursuit of maximum water balance.

Overall, the results support the feasibility of deficit irrigation as a strategy to optimize water use without compromising yield. This is of particular importance in regions characterized by unstable hydrothermal conditions.

### Statistical Analysis

The statistical evaluation of the simulation results was performed using the canopy cover parameter (CC, %) as a key indicator of the crop water balance in the AquaCrop model. The comparison was based on a dataset of  $n = 5$  paired observations. The average value of observed canopy cover amounted to 13.2 %, whereas the simulated mean was 11.8 %, indicating a slight underestimation of CC by the model under the studied conditions.

The obtained statistical indicators demonstrate a high level of agreement between simulated and field data. The correlation coefficient reached  $r = 0.93$ , confirming a strong linear relationship between observed and simulated values. The magnitude of the simulation error was relatively low (RMSE = 2.8 % CC), while the normalized error (CV(RMSE) = 21.1 %) indicates an acceptable level of deviation given the limited number of observations. The value of the model efficiency coefficient (EF = 0.73) suggests good predictive performance of the model, and the high index of agreement ( $d = 0.94$ ) further confirms the close correspondence between simulated and measured canopy cover values. Overall, the statistical indicators demonstrate satisfactory performance of the AquaCrop model in reproducing canopy development dynamics.

### Conclusion

Modeling results identified moisture deficiency during leaf area formation as the main factor limiting grapevine productivity. A high level of canopy expansion stress (40 %) indicated that water supply was insufficient to support intensive early-season leaf development, leading to reduced seasonal transpiration and a biomass deficit of approximately 14%. Physiologically, leaf expansion is significantly more sensitive to water deficit than stomatal regulation, meaning that early-season moisture limitations create a structural “bottleneck”. This reduction in the canopy’s light-intercepting surface establishes a cumulative biomass deficit that persists throughout the season, even if gas exchange remains relatively stable during later stages.

Stomatal closure restricted gas exchange by only 7 %, confirming its short-term and moderate character even during peak summer heat. Thus, productivity losses in July–August were not primarily associated with acute water or heat stress but rather with a structural limitation—slower canopy development early in the season. Heat stress had an estimated effect of only 4 %, suggesting that local high-temperature episodes exerted a relatively minor influence on overall productivity.

The simulated grape yield was  $10.71 \text{ t ha}^{-1}$ , demonstrating that the harvest index remained stable under variable hydrothermal conditions.

These findings support the recommendation to adjust irrigation regimes with an emphasis on maintaining optimal soil moisture during the early stages of vegetation. Such an approach would minimize restrictions on leaf area formation and enhance overall productivity. This strategy is expected to be more effective than intensifying irrigation in midsummer, when the main photosynthetic structures are already established.

### Limitations and Future Research

While the current study provides valuable insights into the simulation of deficit irrigation for wine grapes, several limitations must be acknowledged in order to contextualize the findings and guide future investigations.

**Model Assumptions and Perennial Crop Adaptation.** AquaCrop was originally developed for herbaceous field crops. Although version 7.1 allows the adaptation of the model for perennial woody species, it still employs certain simplifications regarding deep root architecture, secondary woody biomass

accumulation, and the multi-year carry-over effects of water stress that are characteristic of grapevines.

**Temporal and Climatic Variability.** The research is based on data from a single growing season (2024). While this year provided a representative agrometeorological profile for the semi-arid Northern Black Sea region, interannual climatic variability—particularly fluctuations in winter precipitation and the frequency of extreme heatwaves—may influence the generalizability of the identified irrigation requirements.

**Spatial and Varietal Specificity.** The results are specific to the heavy loam Chernozem soils of the Odesa region and the autochthonous variety Odeskyi Chorny. Given the unique physiological traits and drought-tolerance mechanisms of this cultivar, the observed responses to water deficit may not be directly transferable to other wine grape varieties or to different pedoclimatic zones without further calibration.

**Scope of Irrigation Scenarios.** This study focused exclusively on a 50 %  $ET_c$  deficit level, which represents a common management threshold for the region. However, the absence of a broader range of irrigation treatments (e.g., 25 % or 75 %  $ET_c$ ) limits the ability to determine the absolute physiological tipping point for yield loss or water-use optimization.

**Future Research Directions.** Subsequent studies should prioritize multi-year simulations to account for climatic variability and evaluate the performance of additional international and local cultivars. Furthermore, future research should integrate berry quality parameters (such as sugar content, acidity, and the polyphenolic profile) as well as economic cost–benefit analyses to provide more comprehensive recommendations for sustainable viticulture.

## Additional Information and Declarations

**Authors' Contributions:** A. Shtirbu conceived and designed the study; conducted the statistical analysis, and drafted the manuscript. V. Palariiev performed field experiments and collected data. All authors critically revised the manuscript and approved the final version.

**Conflict of Interests:** The authors declare that they have no conflict of interest.



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