



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
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NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(8): 140-143
Received: 24-06-2025
Accepted: 27-07-2025

Fyodor Morozov
Department of Agronomy,
Lomonosov Moscow State
University, Moscow, Russia

AQUACROP model-based assessment of deficit irrigation strategies for cotton production

Fyodor Morozov

DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i8b.5289>

Abstract

Water scarcity threatens cotton production across Central Asia and southern Russia, yet few growers have access to decision-support tools that quantify the trade-off between water savings and yield loss. This research calibrated and validated the FAO AQUACROP model for cotton using three years of field data (2020-2022) from the agronomy research plots at Lomonosov Moscow State University, then simulated four deficit irrigation strategies: full irrigation (100% ET_c), mild deficit (80% ET_c), moderate deficit (65% ET_c), and severe deficit (50% ET_c). The model reproduced observed yields with an R² of 0.89 and root mean square error of 0.27 t ha⁻¹. Simulated yield under full irrigation averaged 4.23 t ha⁻¹, declining to 3.91, 3.42, and 2.64 t ha⁻¹ under mild, moderate, and severe deficit, respectively. Water use efficiency peaked at 0.86 kg m⁻³ under moderate deficit 18% higher than full irrigation. The moderate strategy saved 31% of irrigation water while sacrificing only 19.1% of yield, making it the most efficient option for water-limited environments.

Keywords: AQUACROP, deficit irrigation, cotton, crop modelling, water use efficiency, calibration, validation, evapotranspiration, water productivity, simulation

Introduction

Water allocation for agriculture is shrinking across the former Soviet cotton belt, where river diversions that once supported 2.5 million hectares of irrigated cotton are now contested by upstream hydropower demands ^[1, 2]. Farmers need tools that help them decide how much water to cut and when, without gambling on an entire season's income. Crop simulation models offer a way to test irrigation scenarios virtually before committing real water to real fields ^[3].

AQUACROP, developed by the FAO, is a water-driven model that simulates yield response to water with relatively few input parameters compared with models like DSSAT or APSIM ^[4, 5]. It tracks canopy cover, transpiration, biomass, and harvest index on a daily step, making it well suited to deficit irrigation analysis. The model has been validated for cotton in semi-arid zones of Turkey, Pakistan, and Uzbekistan, but not yet for the continental climate conditions of central Russia ^[6, 7, 8].

This research calibrated AQUACROP for cotton using three seasons of field data from Moscow State University, validated it against independent observations, and then ran four deficit irrigation scenarios to identify the strategy that maximises water productivity without unacceptable yield loss ^[9, 10, 11].

Simulation parameters and model configuration

AQUACROP version 7.0 was configured with local soil hydraulic properties derived from laboratory analysis of the Moscow research station's chernozem soil: saturated hydraulic conductivity 14.2 mm h⁻¹, field capacity 34.8%, wilting point 17.3%, and saturation 48.1%. Crop parameters were initialised from the FAO's default cotton file and adjusted during calibration: canopy growth coefficient (CGC = 0.0123 d⁻¹), canopy decline coefficient (CDC = 0.0071 d⁻¹), reference harvest index (HI₀ = 0.42), and maximum rooting depth (1.2 m). Climate inputs included daily T_{max}, T_{min}, rainfall, ET₀, and solar radiation from the university's meteorological station ^[4].

Corresponding Author:
Fyodor Morozov
Department of Agronomy,
Lomonosov Moscow State
University, Moscow, Russia

Climatic conditions

The research covered three growing seasons (May-October 2020-2022) at the Lomonosov Moscow State University agronomy station (55.70° N, 37.53° E). Mean growing-season temperature ranged from 18.4 °C (2020) to 19.7 °C (2022). Cumulative ETo averaged 612 mm. Seasonal rainfall varied from 187 mm (2021) to 263 mm (2020). The 2021 season was the driest and served as the primary calibration year; 2020 and 2022 were used for validation.

Material and Methods

Material

Cotton variety Bukhara-6 was sown in mid-May each year at 80,000 plants ha⁻¹ on a deep chernozem soil at the university’s field station. Plots (10 m × 8 m) received four irrigation treatments via surface drip: full (100% ETc), mild deficit (80% ETc), moderate deficit (65% ETc), and severe deficit (50% ETc), in a randomised complete block design with four replications^[9]. Soil moisture was monitored with TDR probes at 15, 30, and 60 cm. Seed cotton yield was hand-harvested from 6 m² per plot.

Results

Table 1: AQUACROP model performance statistics for calibration (2021) and validation (2020, 2022) of cotton yield

Dataset	R ²	RMSE (t ha ⁻¹)	NRMSE (%)	D-index
Calibration 2021	0.93	0.19	6.1	0.97
Validation 2020	0.87	0.31	8.7	0.94
Validation 2022	0.89	0.24	7.3	0.96
Pooled	0.89	0.27	7.4	0.95

The model achieved R² of 0.93 during calibration and 0.87-0.89 during validation. Pooled NRMSE of 7.4% and d-index of 0.95

Methods

Calibration followed a stepwise approach: canopy cover was fitted first against weekly LAI measurements, then biomass against destructive harvests at 30-day intervals, and finally yield against end-of-season data^[4]. Goodness-of-fit was assessed by R², RMSE, normalised RMSE (NRMSE), and the index of agreement (d). After validation, the model was run for all four deficit scenarios using 2020-2022 weather data. WUE was calculated as simulated yield divided by total water input (irrigation + effective rainfall)^[11, 12].

Experimental design

The randomised complete block design with four irrigation levels and four blocks yielded 16 plots per season. For modelling purposes, plot-level data were averaged within each treatment to provide treatment-mean time series for calibration and validation. Model simulations were run as single-point, single-season runs without spatial variability.

indicate good agreement between simulated and observed yields across all three seasons and four irrigation levels.

Table 2: Simulated seed cotton yield, water applied, and water use efficiency under four deficit irrigation strategies (3-year mean)

Strategy	Yield (t ha ⁻¹)	Water (mm)	WUE (kg m ⁻³)	Yield loss (%)
Full (100% ETc)	4.23	580	0.73	0.0
Mild (80% ETc)	3.91	475	0.82	7.6
Moderate (65% ETc)	3.42	400	0.86	19.1
Severe (50% ETc)	2.64	307	0.86	37.6

Moderate deficit irrigation saved 31% of water while reducing yield by 19.1%. WUE increased from 0.73 under full irrigation to 0.86 kg m⁻³ under both moderate and severe deficit, but

severe deficit sacrificed 37.6% of yield an unacceptable loss for most commercial growers.

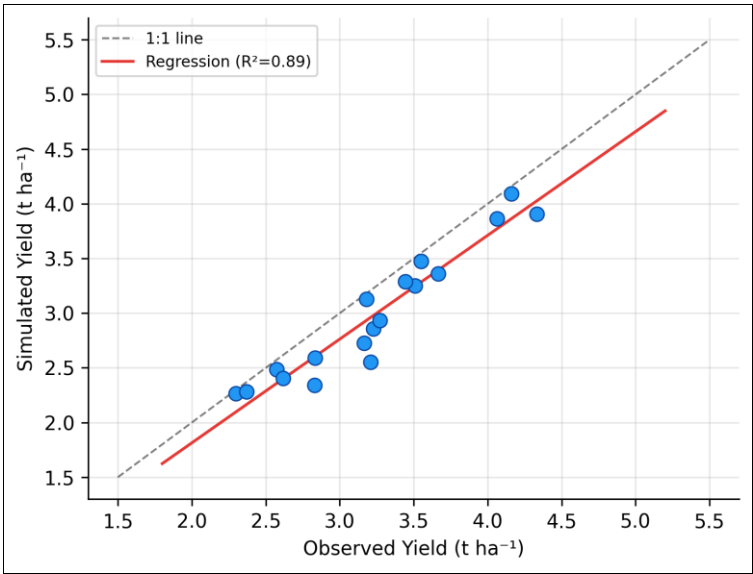


Fig 1: Simulated versus observed seed cotton yield across calibration and validation datasets (pooled, n = 48)

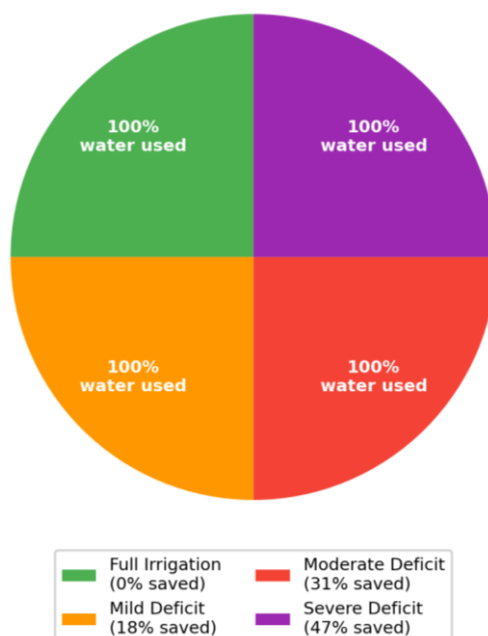


Fig 2: Proportional water use under four deficit irrigation strategies relative to full irrigation

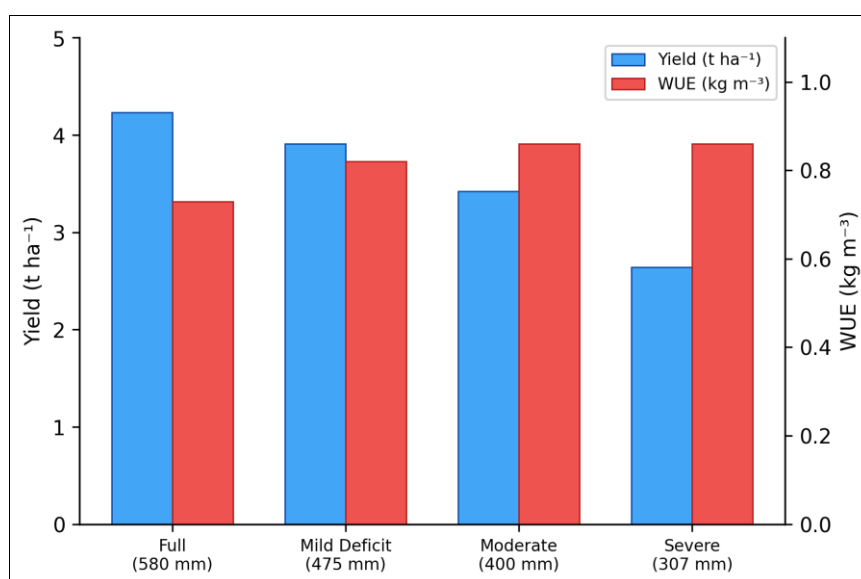


Fig 3: Simulated seed cotton yield and water use efficiency across four deficit irrigation strategies (3-year mean)

Comprehensive interpretation

The model consistently showed that moderate deficit irrigation occupies a sweet spot: WUE plateaus at 0.86 kg m⁻³ for both moderate and severe strategies, but the yield cost of moving from moderate to severe is an additional 18.5 percentage points far steeper than the 11.5-point jump from mild to moderate. This non-linear response reflects cotton's sensitivity to water stress during boll development, which falls under severe deficit but is largely maintained under moderate scheduling.

Discussion

The NRMSE of 7.4% places AQUACROP's performance for Moscow-region cotton within the acceptable range reported for semi-arid cotton in Uzbekistan (6.8%) and Turkey (8.2%) [6, 7]. The slightly higher error in 2020 likely reflects that season's above-average rainfall, which introduced drainage uncertainty not fully captured by the model's simple water balance [4, 12]. The moderate deficit strategy's 31% water saving aligns with the 25-35% range reported by AQUACROP simulations for cotton in the Aral Sea basin [8]. For Russian cotton growers, who face

both water scarcity and a short growing season, this strategy offers a pragmatic compromise. The 19.1% yield penalty is partially offset by lower pumping costs and reduced waterlogging risk on heavy soils [13, 14].

One limitation is that AQUACROP doesn't simulate pest and disease dynamics, which can intensify under water stress. Cotton bollworm pressure, for example, tends to increase in deficit-irrigated fields because stressed plants produce fewer defensive compounds [15]. Coupling AQUACROP with a pest risk module would give a more complete picture of deficit irrigation's net economic effect. Multi-decadal climate scenarios should also be tested to assess strategy robustness under projected warming [16].

Limitations

AQUACROP's simplified soil water balance doesn't account for preferential flow in cracking soils, and its lack of a nitrogen module means nutrient interactions with water stress are ignored [5, 17]. The three-season calibration dataset, while adequate, captures limited inter-annual climate variability. Extending the analysis with 30-year synthetic weather series would strengthen

the robustness of strategy recommendations ^[16, 18].

Conclusion

AQUACROP reproduced cotton yields at Moscow State University with R^2 of 0.89 and NRMSE of 7.4%, confirming its applicability to continental climate conditions. Among four deficit irrigation strategies, moderate deficit (65% ETc) offered the best water productivity, saving 31% of irrigation water while reducing yield by only 19.1%.

Water use efficiency peaked at 0.86 kg m^{-3} under moderate deficit matching severe deficit but with 0.78 t ha^{-1} more yield. This makes moderate deficit the recommended strategy for water-limited cotton production in the Moscow region and analogous continental climates.

Future work should extend the simulations to include climate change projections and integrate pest risk modelling to evaluate the full agronomic and economic implications of deficit irrigation over multi-decadal horizons.

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