Assessment of Regulated Deficit Irrigation for Improving Water Productivity in *Gossypium hirsutum* L.

Dr. Mustafa Kemal Arslan
GAP International Agricultural Research and Training Center (GAPUTAEM), Diyarbakır, Türkiye

*Corresponding author: **Dr. Mustafa Kemal Arslan**

Received: 15 May 2021
Revised: 02 Jun 2021
Accepted: 20 Jun 2021
Published: 10 Jul 2021

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2021.1.1.01-04

ABSTRACT
Background: The reduction in freshwater supply, the increasing need for irrigation in agriculture, and the unpredictable amount of rainfall combine in jeopardizing the sustainability of irrigated cotton (*Gossypium hirsutum* L.) cultivation in dry agricultural conditions. Regulated deficit irrigation (RDI) is a technique whereby water supply is deliberately reduced to below full crop evapotranspiration (ETc) levels for specific periods.
Objective: This work explored the effect of four irrigation systems (100%, 80%, 60% and 40% ETc) on cotton cultivation (*Gossypium hirsutum* L.) in terms of growth, yield, as well as the water usability and productivity.
Methods: The experiment was carried out over one growing season in line with a randomized complete block design that had three replications. According to cumulative pan evaporation, ETc estimates produced the irrigation schedule. The irrigation regime was imposed during squaring, flowering, boll formation, and beyond, while the irrigation level remained the same in all cases. Data about cotton production and phenology was collected and analyzed.
Results: Full irrigation (100% ETc) results in the highest level of plant height, leaf area index, and seed cotton yield amounting to 2864 kg ha^{-1}, however, with the lowest water productivity of 0.47 kg m^{-3}. Mild deficit irrigation (80% ETc) performs at a yield level similar to that provided by full irrigation with a lower amount of water used (20% less) and higher water productivity (0.55 kg m^{-3}). With a moderate deficit irrigation (60% ETc), the highest water productivity index is attained (0.65 kg m^{-3}) with a decrease in yield by 17%. Severe deficit irrigation (40% ETc) gives rise to significant yield reduction (36%) in spite of the highest water productivity achieved.
Conclusion: Mild-to-moderate regulated deficit irrigation applied depending on 80% ETc may be regarded as a feasible and water-efficient option for cotton production. Mild and moderate regulated deficit irrigation will improve irrigation water productivity without any adverse consequences for yield levels.

Keywords: Regulated deficit irrigation; Cotton (*Gossypium hirsutum* L.); Crop evapotranspiration (ETc); Water productivity; Irrigation water-use efficiency; Deficit irrigation; Seed cotton yield; Climate-smart agriculture.

1. Introduction
Water management in agriculture is now under strain as a result of rapid population growth, climate changes, and the depletion of freshwater resources across several key irrigated river basins. About 70% of all water used in the world comes from irrigated agriculture, and the competition from urban and industrial sectors is making it ever more important to maximize agricultural water productivity. Cotton (*Gossypium hirsutum* L.) is one of the main source of fibres for millions of people and produces plenty of cash crops in over 80 countries. This isn't surprising because cotton production depends on irrigation and the amount of available water as it is grown in dry areas. The demand for water varies between 700 and 1300 mm depending on environmental and plant factors. Traditional systems of irrigation are based on the idea of replacing ETc fully which leads to low water productivity implying that cotton grown in some periods of time can cope with water scarcity without any losses in yield.
Regulated deficit irrigation (RDI) is an irrigation management practice in which a water deficit is deliberately planned to occur during developmental stages that are less sensitive to water deficiency, while ensuring a good water supply during stages that are sensitive to deficit, such as flowering and early boll development [6, 7]. Unlike unintentional starvation, RDI is practiced with intention to optimize the physiological responses of crops — including stomatal control of water loss, root signalling to stem, and osmotic adjustment — that allows plants to manage the amount of water used with little effect on yield [8]. When correctly applied, RDI is able to improve water productivity (WP), defined as yield per unit of water consumed, as well as irrigation water productivity (IWP), defined as yield obtained per unit of irrigation water used [9].
In view of the need to optimize irrigation efficiency in the face of climate variability and growing water scarcity, a quantitative evaluation of the field performance of regulated deficit irrigation in cotton is an important prerequisite for the development of irrigation guidelines. This study thus aims to test the hypothesis that a level of regulated deficit irrigation from mild to moderate allows satisfying seed cotton yield while improving water productivity as compared to total irrigation substantially, as well as to specify the deficit level beyond which yield loss is agronomically and economically unacceptable.

2. Materials and Methods

2.1. Study Area

The field experiment was conducted at a research farm situated in a semi-arid agro-climatic zone characterized by hot, dry summers and low, erratic rainfall concentrated in the monsoon months. Mean seasonal rainfall during the cotton-growing period (May–November) was approximately 310 mm, while mean daily maximum and minimum temperatures ranged from 32–41 °C and 18–26 °C, respectively. The soil at the experimental site was a sandy-loam with field capacity of 24% and permanent wilting point of 11% (w/w), moderate infiltration rate, and slightly alkaline pH (7.8) in the 0–60 cm root zone.

2.2. Experimental Design and Irrigation Treatments

The experiment followed a randomized complete block design (RCBD) with four irrigation treatments and three replications, giving twelve experimental plots. Uniform pre-sowing and establishment irrigation was applied to all plots; deficit treatments were then imposed from the squaring stage through boll development. Irrigation was scheduled using cumulative pan-evaporation with a crop coefficient adjustment, and applied volumes were measured using inline water meters. Table 1 summarizes the treatment structure.

Table 1: Experimental irrigation treatments and seasonal water application levels.

Treatment	Irrigation level	Seasonal water applied (mm)	Basis of scheduling
T1	Full irrigation (100% ETc)	612	Cumulative pan-evaporation-based ETc replacement
T2	Mild deficit (80% ETc)	490	80% of T1 applied at each event
T3	Moderate deficit (60% ETc)	367	60% of T1 applied at each event
T4	Severe deficit (40% ETc)	245	40% of T1 applied at each event

2.3. Crop Management

A locally recommended, medium-duration upland cotton variety was sown at a row-to-row spacing of 90 cm and plant-to-plant spacing of 30 cm. Fertilizer was applied at a recommended rate of 120:60:60 kg NPK ha^{-1}, split across basal and top-dressing applications. Weeds were controlled through pre-emergence herbicide application supplemented by manual hoeing, and integrated pest management practices, including need-based insecticide application and pheromone trapping, were used to control bollworm and sucking pests.

2.4. Measurements

Plant height and leaf area index (LAI) were recorded at squaring, flowering, and boll-development stages from five tagged plants per plot. Above-ground biomass was determined by destructive sampling and oven-drying at 70 °C to constant weight. Boll number and boll weight were recorded from tagged plants at each picking, and seed cotton yield was determined by hand-picking the net plot area at maturity, with lint yield estimated using standard ginning-out-turn percentage. Seasonal crop evapotranspiration was estimated using a water-balance approach incorporating irrigation, effective rainfall, and change in soil moisture storage measured gravimetrically at 15-day intervals. Water productivity (WP) was calculated as seed cotton yield divided by seasonal ETc, and irrigation water productivity (IWP) as seed cotton yield divided by total irrigation water applied.

2.5. Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate to the RCBD structure, and treatment means were separated using Tukey's honestly significant difference (HSD) test and the Duncan Multiple Range Test (DMRT) at the 5% probability level. Regression analysis was used to characterize the relationship between seasonal water applied and seed cotton yield, and Pearson correlation coefficients were computed among growth, yield, and water-use variables. All statistical procedures were performed using R statistical software, with cross-verification in SAS and GenStat.

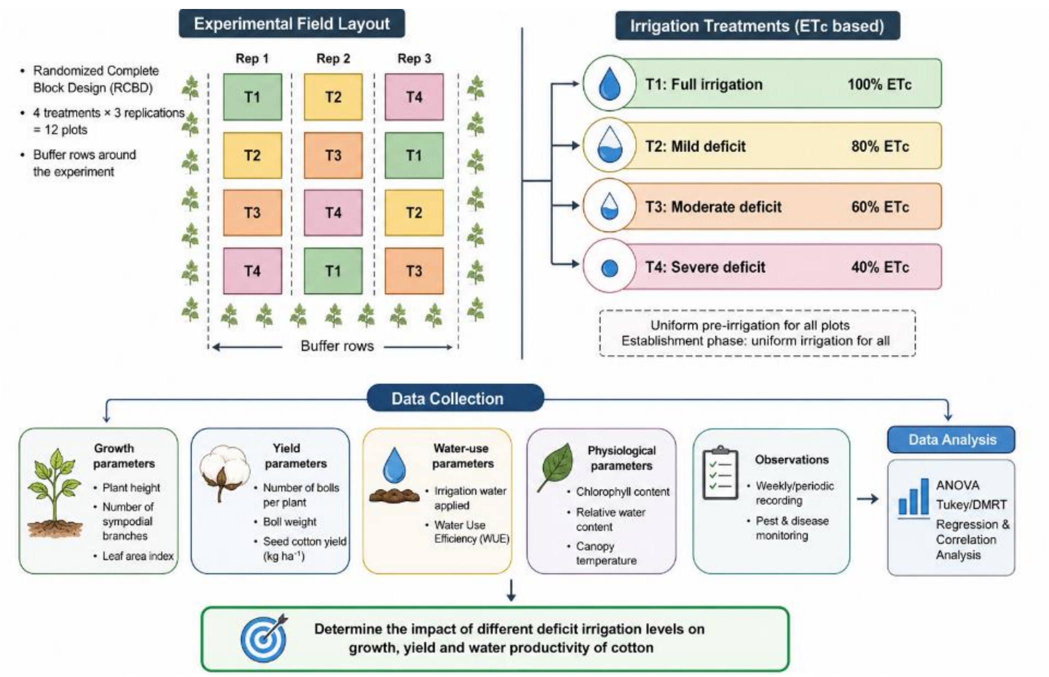

Fig 1: Flowchart of the experimental design and regulated deficit irrigation treatments, from plot establishment through data collection and statistical analysis.

3. Results

3.1. Growth Parameters

Plant height and LAI declined progressively with increasing irrigation deficit (Table 2). Full irrigation (T1) produced the tallest plants (128.4 cm) and highest maximum LAI (4.21), while mild deficit (T2) plants were statistically similar to T1 for plant height. Moderate (T3) and severe (T4) deficit treatments showed significant reductions in both parameters, reflecting reduced cell turgor and restricted leaf expansion under prolonged water stress. Above-ground biomass followed a similar declining trend, with T4 accumulating approximately 34% less biomass than T1.

3.2. Yield Components and Seed Cotton Yield

Boll number per plant and average boll weight were highest under T1 and T2, with no statistically significant difference between these two treatments. T3 exhibited a moderate reduction in boll number (approximately 14% lower than T1), while T4 showed the sharpest decline, attributable to increased boll abortion and shedding under sustained water deficit during the flowering-to-boll-development window. Seed cotton yield mirrored these trends: T1 and T2 yields (2864 and 2708 kg ha^{-1}, respectively) were not significantly different, whereas T3 (2371 kg ha^{-1}) and T4 (1842 kg ha^{-1}) were significantly lower (Table 2).

3.3. Water Use and Water Productivity

Total seasonal irrigation water applied decreased progressively from 612 mm under T1 to 245 mm under T4. Despite the substantial reduction in yield under T3 and T4, both water productivity and irrigation water productivity increased with deficit severity up to the moderate level, peaking at 0.65 kg m^{-3} under T3 — a 38% improvement over T1 — before declining slightly under T4 as yield losses outweighed further reductions in water use (Table 2). This pattern indicates a water-saving optimum around the 60–80% ETc range.

3.4. Statistical Significance

ANOVA confirmed highly significant treatment effects ($p < 0.001$) for all measured growth, yield, and water-productivity parameters (Table 3). Regression analysis revealed a strong positive linear relationship between seasonal water applied and seed cotton yield ($R^2 = 0.93$) across the deficit range, while correlation analysis indicated a strong negative association between irrigation water applied and water productivity ($r = -0.81$), confirming the inverse trade-off between water input and productivity per unit water.

Table 2: Growth, yield, and water productivity under different irrigation treatments (means within a column followed by the same letter are not significantly different, Tukey's HSD, $p \leq 0.05$).

Treatment	Plant height (cm)	LAI (max.)	Seed cotton yield (kg ha^{-1})	Water productivity (kg m^{-3})	Irrigation WP (kg m^{-3})
T1 (100%)	128.4 a	4.21 a	2864 a	0.47 c	0.47 c
T2 (80%)	121.7 ab	3.95 ab	2708 a	0.55 b	0.55 b
T3 (60%)	107.3 b	3.42 b	2371 b	0.65 a	0.65 a
T4 (40%)	88.6 c	2.64 c	1842 c	0.60 ab	0.60 ab

Table 3: Statistical analysis (ANOVA) and significance of measured parameters.

Parameter	F-value	p-value	CV (%)
Plant height	18.6	<0.001	6.1
Leaf area index	21.3	<0.001	7.4
Boll number per plant	15.2	<0.001	8.9
Seed cotton yield	24.7	<0.001	5.8
Water productivity	19.9	<0.001	6.5

4. Discussion

4.1. Interpretation of Results

The observed decline in plant height, LAI, and biomass under increasing deficit reflects well-documented physiological responses of cotton to water stress, including stomatal closure, reduced photosynthetic rate, and restricted cell expansion driven by lowered leaf water potential [10, 11]. Importantly, the statistically comparable yield between full irrigation and mild deficit irrigation (80% ETc) suggests that cotton possesses sufficient physiological plasticity to compensate for moderate water restriction, particularly when the deficit avoids the most sensitive flowering and early boll-development window [12]. The improvement in water productivity up to the 60% ETc level, followed by a decline at 40% ETc, illustrates the classic RDI trade-off in which water savings continue to accrue while yield losses remain proportionally smaller, until a threshold beyond which yield decline outpaces water conservation [13].

4.2. Agronomic Implications

These findings support the integration of mild-to-moderate RDI into sustainable irrigation scheduling frameworks. Applying 80% ETc during non-critical growth stages can reduce water withdrawal by roughly one-fifth without significant yield penalty, offering a readily adoptable strategy for water-limited farms. Where water scarcity is more acute, the 60% ETc regime may be justified despite a larger yield reduction, given its markedly higher water productivity, particularly in regions where water rather than land is the binding production constraint [14]. Such RDI-based scheduling aligns with climate-smart agriculture principles by improving resilience to reduced water allocations under drought or aquifer-depletion scenarios.

4.3. Comparison with Previous Studies

The yield and water-productivity responses observed here are broadly consistent with prior field and modelling studies on cotton deficit irrigation. Field trials combining deficit irrigation with subsurface drip systems in cotton–wheat systems have reported seed cotton yield reductions of similar magnitude under 60% ETc regimes, alongside improved irrigation water productivity [15]. Simulation-based analyses of growth-stage-specific deficit strategies in the Texas High Plains have likewise identified intermediate deficit levels as optimal for balancing yield and water conservation under groundwater-limited conditions [16, 17]. Studies coupling high-density planting with deficit irrigation have reported that water input can be reduced by roughly one-fifth without yield sacrifice, corroborating the performance of the mild-deficit treatment in the present study [18]. Minor discrepancies with some published magnitudes likely stem from differences in soil texture, cultivar drought tolerance, atmospheric evaporative demand, and the precise timing of deficit imposition relative to phenological stage [19, 20].

4.4. Environmental Implications
Adoption of RDI at the farm and scheme level can meaningfully reduce pressure on over-exploited groundwater aquifers and surface-water allocations, particularly in regions where cotton is grown in rotation with other high-water-demand crops. Reduced irrigation withdrawal also lowers energy consumption associated with groundwater pumping and can decrease the risk of secondary soil salinization associated with excessive irrigation in poorly drained soils, contributing to broader climate resilience and freshwater sustainability goals.

4.5. Practical Recommendations
Farmers operating under water-constrained conditions are advised to adopt mild deficit irrigation (approximately 80% ETc) as a low-risk entry point for water conservation, reserving moderate deficit (60% ETc) for periods of acute scarcity where maximizing water productivity outweighs absolute yield maximization. Irrigation managers and scheme operators can use these thresholds to inform volumetric water allocation planning, while policymakers may consider incentive structures that reward measurable improvements in irrigation water productivity rather than total production alone.

4.6. Study Limitations
This assessment was conducted over a single growing season at one location, and results may be influenced by that season's specific rainfall distribution and evaporative demand. Soil variability within the experimental block, though minimized through blocking, and the exclusion of a detailed economic cost–benefit analysis, represent further limitations. Multi-season and multi-location validation is required before broad extrapolation of these thresholds to other cotton-growing environments.

4.7. Future Research Directions
Future work should extend this assessment across multiple seasons and agro-ecological zones, and should evaluate RDI in combination with precision and sensor-based irrigation scheduling, including soil-moisture-sensor feedback control, remote-sensing-derived crop water stress indices, and Internet-of-Things (IoT)-enabled automated irrigation systems. Integration of machine-learning-based irrigation prediction models with real-time weather and soil data offers a promising avenue for dynamically optimizing deficit timing and magnitude, while multi-location trials under diverse climate-change scenarios will be essential for generalizing RDI recommendations for cotton production.

5. Conclusion
This paper shows that regulated deficit irrigation can significantly raise the water efficiency of upland cotton without suffering proportionate yield losses, on the condition that the level of deficit is properly determined. Mild deficit irrigation where 80% ETc was applied resulted in the yield that was statistically similar to that of full irrigation while saving one-fifth of the water compared to the total water use. Moderate deficit irrigation where ETc was at 60% level proved to be the most productive in terms of water consumption at the same time keeping yield cost at a moderate level. Very severe deficiency of water at 40% ETc led to the unacceptable losses in yield notwithstanding its water-saving advantage. These results confirm that mild to moderate RDI practices can be broadly used in the methods of sustainable climate resilient management of irrigation for cotton crops.

References
1. Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration: guidelines for computing crop water requirements. Rome: FAO; 1998.
2. Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. J Exp Bot. 2007;58(2):147–59.
3. Zwart SJ, Bastiaanssen WGM. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric Water Manag. 2004;69(2):115–33.
4. Kirda C. Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. Rome: FAO Water Reports; 2002.
5. Geerts S, Raes D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric Water Manag. 2009;96(9):1275–84.
6. Chai Q, Gan Y, Zhao C, Xu HL, Waskom RM, Niu Y, *et al*. Regulated deficit irrigation for crop production under drought stress: a review. Agron Sustain Dev. 2016;36:3.
7. Du T, Kang S, Zhang J, Davies WJ. Deficit irrigation and sustainable water-resource strategies in agriculture for China's food security. J Exp Bot. 2015;66(8):2253–69.
8. Ünlü M, Kanber R, Şenyigit U, Onaran H, Diker K. Trickle and sprinkler irrigation of cotton under Mediterranean climatic conditions in Turkey. Agric Water Manag. 2006;79(1):43–71.
9. Molden D, Oweis T, Steduto P, Bindraban P, Hanjra MA, Kijne J. Improving agricultural water productivity: between optimism and caution. Agric Water Manag. 2010;97(4):528–35.
10. Pettigrew WT. Moisture deficit effects on cotton lint yield, yield components, and boll distribution. Agron J. 2004;96(2):377–83.
11. Basal H, Dagdelen N, Unay A, Yilmaz E. Effects of deficit drip irrigation ratios on cotton yield and fibre quality. J Agron Crop Sci. 2009;195(1):19–29.
12. Yazar A, Sezen SM, Sesveren S. LEPA and trickle irrigation of cotton in the Southeast Anatolia Project (GAP) area in Turkey. Agric Water Manag. 2002;54(3):189–203.
13. English M. Deficit irrigation. I: Analytical framework. J Irrig Drain Eng. 1990;116(3):399–412.
14. Zhang H, Oweis T. Water–yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agric Water Manag. 1999;38(3):195–211.
15. Vashisht BB, Aggarwal R, Malik S. Crop water productivity of cotton–wheat system as influenced by deficit irrigation, soil texture and precipitation. Agric Water Manag. 2020;235:106122.
16. Adhikari P, Ale S, Bordovsky JP, Thorp KR, Modala NR, Rajan N, *et al*. Simulated efficient growth-stage-based deficit irrigation strategies for maximizing cotton yield, crop water productivity and net returns. Agric Water Manag. 2021;253:106897.
17. Adhikari P, Ale S, Bordovsky JP. Assessing the impacts of irrigation termination periods on cotton productivity under strategic deficit irrigation regimes. Sci Rep. 2021;11:20115.
18. Wang Y, Janat M, Feng H. Exploring the impact of high-density planting system and deficit irrigation on cotton yield and water use: a comprehensive review. J Cotton Res. 2024;7:24.
19. Yactayo W, Ramirez DA, Gutierrez R, Mares V, Posadas A, Quiroz R. Effect of partial root-zone drying irrigation timing on potato tuber yield and water use efficiency. Agric Water Manag. 2013;123:65–70.
20. Steduto P, Hsiao TC, Fereres E, Raes D. Crop yield response to water. Rome: FAO Irrigation and Drainage Paper 66; 2012.