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IMPROVING WATER USE EFFICIENCY OF FIELD CROPS THROUGH REGULATED DEFICIT IRRIGATION

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SUMMARY - Deficit irrigation occurrence while maintaining acceptable yield represents a useful trait for crop production wherever irrigation water is limited. A seven year experiment (1998-2004) was conducted at Tal Amara Research Station in the Bekaa Valley of Lebanon to determine water use, yield and water use efficiency in four annual crops; maize (1998-1999); soybean (2000-2001); cotton (2001-2002) and sunflower (2002-2003). Reference evapotranspiration ($ET_{rye\text{-}grass}$) and crop evapotranspiration (ET_{crop}) were measured each in a set of two drainage lysimeters of 2m×2m×1m size cultivated with rye grass (*Lolium perenne*). Crop evapotranspiration (ET_{crop}) was measured using weighing and drainage lysimeters of different sizes. In the plots, evapotranspiration (ET) was measured using a simple soil water balance model. Crop coefficients (K_c) in the different crop growth stages were derived as the ratio ($ET_{crop}/ET_{rye\text{-}grass}$). At harvest, $1m^2$ quadrates were sampled randomly from the different irrigation treatments to determine yield and its components. Water use efficiency at grain (WUE_g) and seed (WUE_s) bases was calculated as the ratio of dry yield to crop evapotranspiration (Y/ET), while water use efficiency at biomass-basis (WUE_b) was calculated as the ratio of dry biomass to ET (B/ET). Water use efficiency of cotton (WUE_l) was calculated as the ratio of lint yield at dry basis to evapotranspiration.

Maize seasonal ET reached on the lysimeter 952 mm in 1998 and 920 mm in 1999. Water use efficiency at grain basis (WUE_g) varied among maize treatments from 1.34 kg m^{-3} to 1.88 kg m^{-3}, while at biomass basis WUE_b varied from 2.34 kg m^{-3} to 3.23 kg m^{-3}. Soybean seasonal ET totaled 800 mm in 2000 and 725 mm in 2001. Seed-related water use efficiency (WUE_s) of soybean varied from 0.47 kg m^{-3} to 0.54 kg m^{-3}, at biomass basis WUE_b varied from 1.06 to 1.16 kg m^{-3}. Cotton seasonal ET was 641.5 mm in 2001 and 669.0 mm in 2002 and WUE_l varied among treatments from 0.43 kg m^{-3} to 0.64 kg m^{-3}, while WUE_b varied from 1.82 to 2.16 kg m^{-3}. Sunflower seasonal ET attained 765 mm in 2003 and 882 mm in 2004 and WUE_s varied from 0.71 kg m^{-3} to 0.83 kg m^{-3}, while WUE_b varied from 3.46 kg m^{-3} to 4.1 kg m^{-3}. Finally, results showed that deficit irrigation at mature seeds in soybean was more profitable compared to full bloom and seed enlargement. Moreover, flowering was the most critical stage of sunflower to deficit irrigation and therefore deficit irrigation at this stage should be avoided, while it can be acceptable at seed formation. For cotton, timing irrigation deficit at first open boll has been found to provide the highest lint yield with maximum WUE, in comparison to deficit irrigation at early boll loading and mid boll loading. For maize, deficit irrigated-treatment produced less seed yield but resulted in higher water use efficiency that the well irrigated control.

Key words: Reference Evapotranspiration, Crop Evapotranspiration, crop coefficients, lysimeter, yield, biomass, WUE.

INTRODUCTION

Regulated deficit irrigation (RDI) is a common practice in many areas of the world (English and Raja, 1996). A number of studies have analyzed the economics of deficit irrigation in specific circumstances and have concluded that this technique can increase net farm income (English, 1990). The potential benefits of deficit irrigation derive from three factors; increased irrigation efficiency, reduced costs of irrigation and the opportunity costs of water.

Regulated deficit irrigation (RDI) may be implemented during part of the growing season by regulating moisture within a desired deficit range. RDI aims to optimize water use efficiency and therefore maximize the yield returned per unit of water applied. Any minor yield loss, which may result from the implementation of a mild moisture deficit/stress under RDI, is offset by the benefits of reduced water use leading to a reduction in excessive vegetative growth (Kirnak et al., 2002). A variety of crops have been found to benefit from a RDI strategy including maize, wheat, sunflower, potatoes, tomatoes and cotton. Irrigation using drip is typically able to apply smaller quantities of water more frequently, and is better able to maintain soil moisture at the mild deficit required to implement RDI.

The objectives of this study were to determine water use and yield in four annual crops with contrasting response to regulated deficit irrigation; maize, soybean, cotton, and sunflower, and to examine the existing relationships between yield and biomass, in one hand, and evapotranspiration in the other hand.

MATERIAL AND METHODS

Field studies aiming at examining the response of maize (*Zea mays* L.), Soybean (*Glycine max* L. Merril), cotton (*Gossypium hirsutum* L.) and sunflower (*Helianthus annuus* L.) to deficit irrigation stress were conducted during the period 1998-2003 at Tal Amara Research Station in the Central Bekaa Valley of Lebanon (33° 51' 44" N lat., 35° 59' 32" E long., altitude 905 m a.s.l). Tal Amara has a well-defined hot, dry season from May to September and very cold for the remainder of the year. Long-run data indicate an average seasonal rain of 592 mm, with 95% of the rain occurring between November and March. Crops were grown on deep and fairly drained soil, characterized by high clay content (44%). Measured field capacity (-0.33 bar) and permanent wilting point (-15 bars) averaged 29.5% and 16.0% by weight. Extractable plant water is estimated at 190 mm for 1 m rooting depth and a bulk density of 1.41 g cm^{-3}.

Hybrid maize (*cv. Manuel*) was sown on 19 May in 1998 and 25 May in 1999 at 10 plants m^{-2}. Soybean hybrid (*cv*. Asgrow 3803) was sown on 10 May 2000 and 25 April 2001 at a density of 12 plants m^{-2}. Cotton (*cv*. AgriPro AP 7114) was sown on 5 May in 2001 and on 13 May in 2002 at a density of 10 plants m^{-2}. Sunflower (*cv*. Arean) was sown on 20 May 2003 and 10 May 2004 at a density of 10 plants m^{-2}.

For maize, crop evapotranspiration (ET_{crop}) was measured using a set of two drainage lysimeters of 4 m^2 surface area (2m×2m) by subtracting the volume of drainage from the irrigation amount. The lysimeter, 1.2 m deep, 24 m apart, aligned N-S, are situated in the middle of 1-ha field (200 m N-S by 50 m W-E) (Karam et al., 2003). For soybean, ET was measured by a weighing lysimeter of 16 m^2 surface area (4m×4m) and 1.2 m deep, containing the same clay soil as in the drainage lysimeters. Watering of the lysimeter was made upon a 30% soil depletion of the available water in the 0-100 cm soil layer. The weight loss of the lysimeter due to soil evaporation and plant transpiration was measured with load cells and recorded at a 15-minute interval on a computer located near the lysimeter. For cotton and sunflower, ET_{crop} was estimated using the FAO method (Doorendos and Pruit, 1977) by multiplying reference evapotranspiration ($ET_{rye\text{-}grass}$) by crop coefficients (K_c):

$$ET = ET_{rye\text{-}grass} \times K_c \quad (1)$$

Reference evapotranspiration ($ET_{rye\ grass}$) was measured in a set of two rye-grass drainage lysimeters of 4 m^2 surface area (2m×2m) and 1m depth. The lysimeters are 24 m distant, aligned W-E, and located inside the weather station (40 m × 40 m), 50 m apart of the experimental plots. *Table 1* illustrates deficit irrigation treatments for the crops under study.

Table 1. Irrigation treatments of the different crops under study

Crop	Year	Treatment	Period of irrigation cutout
Maize	1998 and 1999	I-100	No irrigation restriction during the growing period
		I-60	Deficit irrigation at 40% of crop evapotranspiration (from 6-leaf stage onwards)
Soybean	2000 and 2001	C	No irrigation restriction during the growing period
		S-1	Deficit irrigation at full bloom
		S-2	Deficit irrigation at seed enlargement
		S-3	Deficit irrigation at mature seeds
Cotton	2001 and 2002	C	No irrigation restriction during the growing period
		S-1	Deficit irrigation at first open boll
		S-2	Deficit irrigation at early boll loading
		S-3	Deficit irrigation at mid boll loading
Sunflower	2003 and 2004	C	No irrigation restriction during the growing period
		S-1	Deficit irrigation at early flowering stage
		S-2	Deficit irrigation at mid flowering stage
		S-3	Deficit irrigation at early seed formation

At physiological maturity, all individual plants in the 1m^2 sampling quadrates were harvested to determine above ground biomass production (B) and yield (Y). For maize, grain number per m^2 and the 1000-grain weight were determined. For soybean and sunflower, seed number per m^2 and the 1000-seed weight were also determined. For cotton, yield was determined by weighting lint at dry basis in the sampling areas.

In maize, soybean and sunflower, water use efficiency at grain or seed-basis ($WUE_{g,s}$) was calculated as the ratio of yield at dry basis to crop evapotranspiration (Y/ET), while water use efficiency at biomass-basis (WUE_b) was calculated as the ratio of biomass at dry basis to ET (B/ET). In cotton, water use efficiency at lint-basis (WUE_l) was calculated as dry lint yield to the amount of water evapotranspired from the crop. WUE was expressed in kg m^{-3} (1 kg m^{-3} = 1 g m^{-2} mm^{-1}).

RESULTS AND DISCUSSION

Tables 2, 3 and *4* illustrate crop coefficients of soybean, cotton and sunflower during the growing periods, while *Table 5* shows the values of evapotranspiration (ET), yield (Y), biomass (B) and water use efficiency of the crops under well and deficit irrigation conditions.

Table 2. Reference evapotranspiration ($ET_{rye\text{-}grass}$), evapotranspiration of soybean (ET_{crop}) and crop coefficients (K_c)

	d.a.s	$ET_{rye\text{-}grass}$ (mm)	$ET_{rye\ grass}$ (mm day^{-1})	ET_{crop} (mm)	ET_{crop} (mm day^{-1})	K_c
Dates in 2000						
10-May	0	17.50	2.50	2.80	0.40	0.16
17-May	7	21.70	3.10	11.20	1.60	0.52
24-May	14	27.02	3.86	15.82	2.26	0.59
31-May	21	31.50	4.50	21.00	3.00	0.67
7-Jun	28	35.70	5.10	24.50	3.50	0.69
14-Jun	35	37.80	5.40	26.60	3.80	0.70
21-Jun	42	39.90	5.70	30.10	4.30	0.75
28-Jun	49	42.00	6.00	31.50	4.50	0.75
5-Jul	56	53.34	7.62	44.94	6.42	0.84
12-Jul	63	54.25	7.75	46.20	6.60	0.85
19-Jul	70	55.86	7.98	49.98	7.14	0.89
26-Jul	77	59.50	8.50	54.95	7.85	0.92
2-Aug	84	66.50	9.50	62.44	8.92	0.94
9-Aug	91	66.50	9.50	67.20	9.60	1.01
16-Aug	98	68.74	9.82	64.40	9.20	0.94
23-Aug	105	66.29	9.47	56.00	8.00	0.84
30-Aug	112	65.10	9.30	52.50	7.50	0.81
6-Sep	119	61.04	8.72	49.00	7.00	0.80
13-Sep	126	55.02	7.86	42.00	6.00	0.76
20-Sep	133	39.97	5.71	28.00	4.00	0.70
27-Sep	140	34.02	4.86	18.90	2.70	0.56
Total/Average		999.25	6.80	800.03	5.44	0.75
Dates in 2001						
25-Apr	0	19.74	2.82	6.44	0.92	0.33
30-Apr	5	37.80	5.40	14.00	2.00	0.37
7-May	12	39.20	5.60	17.50	2.50	0.45
14-May	19	42.70	6.10	21.00	3.00	0.49
21-May	26	48.30	6.90	24.50	3.50	0.51
28-May	33	49.70	7.10	26.60	3.80	0.54
4-Jun	40	50.40	7.20	28.00	4.00	0.56
11-Jun	47	56.07	8.01	32.62	4.66	0.58
18-Jun	54	56.14	8.02	32.83	4.69	0.58
25-Jun	61	63.70	9.10	40.67	5.81	0.64
3-Jul	68	64.82	9.26	41.51	5.93	0.64
9-Jul	75	63.70	9.10	47.60	6.80	0.75
16-Jul	82	58.31	8.33	52.15	7.45	0.89
23-Jul	89	59.92	8.56	60.20	8.60	1.00
30-Jul	96	56.00	8.00	57.40	8.20	1.03
6-Aug	103	54.04	7.72	51.80	7.40	0.96
13-Aug	110	53.13	7.59	49.70	7.10	0.94
20-Aug	117	50.82	7.26	40.25	5.75	0.79
27-Aug	124	50.05	7.15	31.50	4.50	0.63
3-Sep	131	45.92	6.56	28.00	4.00	0.61
10-Sep	138	36.47	5.21	21.14	3.02	0.58
Total/Average		1056.93	7.19	725.41	4.93	0.66

Table 3. Reference evapotranspiration ($ET_{rye\text{-}grass}$), evapotranspiration of cotton (ET_{crop}) and measured crop coefficient (K_c)

Irrigation date	$ET_{rye\text{-}grass}$ (mm)	$ET_{rye\text{-}grass}$ (mm day^{-1})	ET_{crop} (mm)	ET_{crop} (mm day^{-1})	Calculated K_c
5-May-01	28.80	4.11	7.80	1.11	0.27
12-May-01	31.10	4.44	10.80	1.54	0.35
19-May-01	38.40	5.49	17.80	2.54	0.46
26-May-01	42.30	6.04	20.60	2.94	0.49
2-Jun-01	45.90	6.56	24.94	3.56	0.54
9-Jun-01	47.59	7.22	28.94	4.13	0.61
16-Jun-01	50.52	7.69	32.26	4.61	0.64
23-Jun-01	53.80	9.76	37.06	5.29	0.69
30-Jun-01	58.26	9.08	43.86	6.27	0.75
7-Jul-01	63.56	9.95	48.94	6.99	0.77
14-Jul-01	68.30	6.80	57.84	8.26	0.85
21-Jul-01	69.68	8.32	76.49	10.93	1.10
28-Jul-01	48.37	6.91	54.73	7.82	1.13
4-Aug-01	31.10	4.44	35.76	5.11	1.15
11-Aug-01	29.39	4.20	33.80	4.83	1.15
18-Aug-01	28.36	4.05	27.51	3.93	0.97
25-Aug-01	29.32	4.19	27.27	3.90	0.93
1-Sep-01	24.11	3.44	21.46	3.07	0.89
8-Sep-01	22.83	3.26	18.49	2.64	0.81
16-Sep-01	21.04	3.01	15.15	2.16	0.72
Total/average	832.73	5.95	641.50	4.58	0.77

Table 4. Reference evapotranspiration ($ET_{rye\ grass}$), evapotranspiration of sunflower (ET_{crop}) and measured crop coefficients (K_c)

	Phenology		$ET_{rye-grass}$		ET_{crop}		K_c	
			(mm)	(mm day^{-1})	(mm)	(mm day^{-1})	Averages	
Year 2003								
From 20 May to 26 May	Crop establishment	Stages A1-A2	30.0	4.3	5.0	0.7	0.17	
From 27 May to 2 June			32.5	4.6	10.0	1.4	0.31	0.24
From 3 June to 9 June	Early vegetative growth	Stages B3 to E1	35.0	5.0	15.0	2.1	0.43	
From 10 June to 16 June			37.5	5.4	20.0	2.9	0.53	
From 17 June to 23 June			40.0	5.7	25.0	3.6	0.63	
From 24 June to 30 June			42.5	6.1	30.0	4.3	0.71	0.57
From 1 July to 7 July	Late vegetative growth	Stages E2 to E4	45.0	6.4	35.0	5.0	0.78	
From 8 July to 14 July			47.5	6.8	40.0	5.7	0.84	
From 15 July to 21 July			50.0	7.1	45.0	6.4	0.90	
From 22 July to 28 July			52.5	7.5	50.0	7.1	0.95	0.87
From 29 July to 4 August	Flowering	Stages F1 to F3.2	55.0	7.9	60.0	8.6	1.09	
From 5 August to 11 August			60.0	8.6	70.0	10.0	1.17	
From 12 August to 18 August			62.5	8.9	80.0	11.4	1.28	
From 19 August to 25 August			70.0	10.0	90.0	12.9	1.29	1.21
From 26 August to 1 September	Seed formation	Stages M0 to M4	50.0	7.1	70.0	10.0	1.40	
From 2 September to 8 September			45.0	6.4	50.0	7.1	1.11	
From 9 September to 15 September			40.0	5.7	35.0	5.0	0.88	
From 16 September to 22 September			35.0	5.0	20.0	2.9	0.57	
From 23 September to 29 September			30.0	4.3	10.0	1.4	0.33	
From 30 September to 6 October			25.0	3.6	5.0	0.7	0.20	0.75
Total/Average			885.0	6.3	765.0	5.5	0.78	0.78

Table 4 (continued)

	Phenology		$ET_{rye\text{-}grass}$		ET_{crop}		Kc	
			(mm)	(mm day^{-1})	(mm)	(mm day^{-1})	Averages	
Year 2004								
From 10 May to 16 May	Crop establishment	Stages A1-A2	25.0	3.6	6.0	0.9	0.24	
From 17 May to 23 May			30.0	4.3	12.0	1.7	0.40	0.32
From 24 May to 30 May	Early vegetative growth	Stages B3 to E1	35.0	5.0	18.0	2.6	0.51	
From 31 May to 6 June			40.0	5.7	24.0	3.4	0.60	
From 7 June to 13 June			45.0	6.4	30.0	4.3	0.67	
From 14 June to 19 June			50.0	7.1	36.0	5.1	0.72	0.63
From 20 Jun to 26 Jun	Late vegetative growth	Stages E2 to E4	55.0	7.9	42.0	6.0	0.76	
From 27 June to 3 July			58.0	8.3	48.0	6.9	0.83	
From 4 July to 10 July			60.0	8.6	60.0	8.6	1.00	
From 11 July to 17 July			62.0	8.9	63.0	9.0	1.02	0.90
From 18 July to 24 July	Flowering	Stages F1 to F3.2	66.0	9.4	73.0	10.4	1.11	
From 25 July to 31 July			68.0	9.7	83.0	11.9	1.22	
From 1 August to 7 August			66.0	9.4	88.0	12.6	1.33	
From 8 August to 14 August			64.0	9.1	94.0	13.4	1.47	1.28
From 15 August to 21 August	Seed formation	Stages M0 to M4	65.0	9.3	74.0	10.6	1.14	
From 22 August 28 August			64.0	9.1	54.0	7.7	0.84	
From 29 August to 4 September			60.0	8.6	39.0	5.6	0.65	
From 5 September to 11 September			52.0	7.4	24.0	3.4	0.46	
From 12 September to 18 September			50.0	7.1	14.0	2.0	0.28	0.56
Total/Average			1015.0	7.6	882.0	6.6	0.80	0.80

Table 5. Crop evapotranspiration, yield, biomass and water use efficiency of different treatments

Crop	Variety	Year	Treatment	ET	Yield	Biomass	WUE_y	WUE_b
				(mm)	(t ha^{-1})	(t ha^{-1})	(kg m^{-3})	(kg m^{-3})
Maize*	Manuel	1998	Lysimeter	952.0	15.2	28.6	1.60	3.00
			I-100	863.0	14.5	27.3	1.68	3.16
			I-60	575.0	10.8	18.6	1.88	3.23
		1999	Lysimeter	920.0	13.4	21.5	1.46	2.34
			I-100	833.0	12.8	20.5	1.54	2.46
			I-60	556.0	10.4	16.5	1.87	2.97
Soybean**	Asgrow 3803	2000	Lysimeter	800.0	3.38	7.96	1.95	4.61
			C	720.0	2.82	6.88	1.81	4.43
			S-1	596.0	2.50	5.66	1.94	4.40
			S-2	632.0	1.76	6.21	1.29	4.55
			S-3	647.0	2.57	6.64	1.84	4.75
		2001	Lysimeter	725.0	3.65	8.23	2.33	5.26
			C	652.0	3.59	7.65	2.55	5.43
			S-1	541.0	3.65	6.53	3.12	5.59
			S-2	580.0	2.93	7.38	2.34	5.89
			S-3	567.0	3.43	7.50	2.80	6.12
Cotton***	AgriPro AP7114	2001	Lysimeter	-	-	-	-	-
			C	577.4	0.4233	2.47192	0.34	1.98
			S-1	473.9	0.6534	1.90098	0.64	1.86
			S-2	537.6	0.5682	2.11622	0.49	1.82
			S-3	542.6	0.5398	2.16691	0.46	1.85
		2002	Lysimeter	-	-	-	-	-
			C	602.2	0.4906	2.80900	0.35	2.16
			S-1	482.9	0.6239	2.16020	0.61	2.07
			S-2	531.8	0.5856	2.40480	0.50	2.09
			S-3	569.6	0.5535	2.46240	0.44	2.00
Sunflower	Arena	2003	Lysimeter	-	-	-	-	-
			C	688.0	5.46	19.2	0.79	3.39
			S-1	534.0	3.95	16.6	0.74	3.16
			S-2	579.0	4.63	17.6	0.80	3.34
			S-3	629.0	5.59	19.6	0.89	3.68
	Arena	2004	Lysimeter	-	-	-	-	-
			C	769.1	5.26	20.5	0.68	4.18
			S-1	598.0	4.06	16.4	0.68	3.76
			S-2	647.0	4.65	18.2	0.72	4.05
			S-3	700.0	5.41	20.6	0.77	4.46

* Karam et al. (2003)
** Karam et al. (2005)
*** Karam et al. (2006)

Grain-related water use efficiency (WUE_g) of lysimeter grown maize was 1.52 kg m^{-3} in 1998 and 1.34 kg m^{-3} in 1999. However, fully irrigated maize had a WUE_g of 1.68 kg m^{-3} in 1998 and 1.54 kg m^{-3} in 1999. Higher WUE_g values of 1.88 kg m^{-3} and 1.87 kg m^{-3} were obtained in 1998 and 1999, respectively, from the I-60 treatment. On a biomass basis, I-100 treatment had values of water use efficiency (WUE_b) of 3.16 kg m^{-3} and 2.46 kg m^{-3} in 1998 and 1999, respectively, while the I-60 treatment had values of 3.23 kg m^{-3} and 2.97 kg m^{-3}, respectively. On the lysimeter, these values were 3.0 kg m^{-3} and 2.34 kg m^{-3}, respectively.

Seed-related water use efficiency (WUE_s) of the well-irrigated soybean treatment was 0.47 kg m^{-3}, showing no consistent difference with the lysimeter grown soybean. Apparently in this experiment, WUE_y of the deficit-irrigated treatments S1 and S3 were 13% and 4% higher than the control. However, the S2 treatment had a WUE_s value 17% lower than the control. For the biomass-basis, water use efficiency (WUE_b) of the control averaged 1.06 kg m^{-3}, whereas WUE_b of treatments S2 and S3 were 6% and 9% higher, respectively. No significant difference was found between treatment S1 and the control.

The highest lint water use efficiency (WUE_l) was encountered for cotton in S1 treatment, and averaged 0.62 kg m^{-3}, followed by S2 (0.50 kg m^{-3}), S3 (0.46 kg m^{-3}) and the control (0.36 kg m^{-3}). These values are very close to those obtained by Gilham et al., (1995). At biomass basis, WUE_b varied from 2.07 kg m^{-3} in the control, to 1.97 kg m^{-3} in S1 treatment, to 1.96 kg m^{-3} in S2 and 1.93 kg m^{-3} in S3.

Average seed-related water use efficiency (WUE_s) of sunflower fully irrigated control an average of 0.80 kg m^{-3} while WUE_s values of the deficit-irrigation treatments were 0.76, 0.81, and 0.87 kg m^{-3}, in S1, S2 and S3, respectively. At biomass basis, WUE_b varied from 3.79 kg m^{-3} in the control, to 3.46 kg m^{-3} in S1 treatment, to 3.70 kg m^{-3} in S2 and 4.07 kg m^{-3} in S3.

CONCLUSIONS

The results obtained in this experiment showed that deficit irrigation at mature seeds in soybean was more profitable compared to full bloom and seed enlargement. Moreover, flowering was the most critical stage of sunflower to deficit irrigation and therefore deficit irrigation at this stage should be avoided, while it can be acceptable at seed formation. For cotton, timing irrigation deficit at first open boll has been found to provide the highest lint yield with maximum WUE, in comparison to deficit irrigation at early boll loading and mid boll loading. For maize, deficit irrigated-treatment produced less seed yield but resulted in higher water use efficiency that the well irrigated control. Moreover, the relationship between yield and ET is an appropriate framework to investigate the pattern of regulated deficit irrigation. Furthermore, these two variables bring forth the variable water use efficiency, i.e. $WUE = YET^{-1}$, a concept widely used in agronomic and irrigation research.

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