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EFFECTS OF DEFICIT IRRIGATION ON YIELD AND WATER USE EFFICIENCY OF SOME CROPS UNDER SEMI-ARID CONDITIONS OF THE BEKAA VALLEY OF LEBANON

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SUMMARY - A six-year experiment (1998-2003) 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 with contrasting response to deficit irrigation (DI); maize (1998-1999) a determinate species with a limited capacity to adjust grain yield in response to water availability; soybean (2000-2001), an indeterminate species with a high capacity to compensate the effects of early water stresses; cotton (2001-2002), an indeterminate species with a larger capacity to adjust the number of dehiscent bolls under stressful conditions, and sunflower (2002-2003), a determinate species with a single inflorescence and an aptitude to tolerate moderate water stresses.

Crop evapotranspiration (ET) was measured using drainage and weighing lysimeters. In the plots, ET was measured using a simple soil water balance model. Yield and its components were determined in sampling areas reserved for harvest. Water use efficiency at grain (WUE_g) or seed (WUE_s) basis 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). For cotton, water use efficiency (WUE_l) was calculated as the ratio of dry lint yield to ET. Furthermore, the relationships between yield (Y) and biomass (B) in one hand, and crop evapotranspiration (ET) in the other hand were examined using linear models. Results of the experiments showed that corn seasonal ET reached on the lysimeter 952 mm in 1998 and 920 mm in 1999. Furthermore, grain-related water use efficiency (WUE_g) varied with corn treatments from 1.34 kg m^{-3} to 1.88 kg m^{-3}, while at biomass-basis (WUE_b) the values varied from 2.34 kg m^{-3} to 3.23 kg m^{-3}. For soybean, seasonal ET totaled 800 mm in 2000 and 725 mm in 2001. Seed-related water use efficiency of soybean (WUE_s) varied from 0.47 kg m^{-3} to 0.54 kg m^{-3}, while WUE_b varied from 1.06 to 1.16 kg m^{-3}. For Cotton, seasonal ET was 641.5 mm in 2001 and 669.0 mm in 2002. Average WUE_l values 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}. For sunflower, average across years of evapotranspiration attained 827 mm. WUE_s of sunflower varied among treatments from 0.64 kg m^{-3} to 0.86 kg m^{-3}, while at biomass-basis WUE_b varied from 3.23 kg m^{-3} to 4.8 kg m^{-3}. The results also showed that yield and biomass have positive, though weak, relationships with ET in corn and soybean, while in cotton and sunflower the relationships are negatives.

Key words: Drainage lysimeter, weighing lysimeter, crop evapotranspiration, yield, biomass, water use efficiency.

INTRODUCTION

Water is fast becoming an economically scare resource in many areas of the world. The need for more efficient agricultural use of irrigation water arises out of increased competition for water resources and increasing environmental concern (Doorenbos and Kassam 1988).

The best use of water must be made for efficient crop production and higher yields. Therefore, agriculture under unfavorable climatic conditions and limited water resources can not be profitably practiced unless on-farm water management techniques are designed to meet the present growing demands of water for increased food production (Oad et al., 2001).

It is necessary therefore to develop new irrigation scheduling approaches, not necessarily based on full crop water requirement, but ones designed to ensure the optimal use of allocated water. Deficit irrigation (or regulated deficit irrigation, RDI) is one way of maximizing water use efficiency (WUE) for higher yields per unit of irrigation water applied (English et al., 1990; English and Raja, 1996; Kirda et al., 1999). The crop is exposed to a certain level of water stress either during a particular growth period or throughout the whole growing season, without significant reductions in yields. The main objective of deficit irrigation is to increase the WUE of a crop by eliminating irrigations that have little impact on yield. The resulting yield reduction may be small compared to the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

In some irrigation schemes, the system is designed to deliver full irrigation in order to meet full crop water demands (Walker and Skogerbe, 1987). In others, the system is designed upon minimum allowable soil water depletion (James, 1988; Keller and Bleisner, 1990). Cuenca (1989) introduced for the first time the concept of partial irrigation within an irrigation scheme, and suggested that under some circumstances the designer might allow for greater soil water depletion, which could result in reduced yields as an economic tradeoff against the higher costs of intensive irrigation water.

Deficit irrigation is a common practice in many areas of the world (English and Raja, 1996). A number of researchers have analyzed the economics of deficit irrigation in specific circumstances and have concluded that this technique can increase net farm income (Martin et al., 1989; 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. Four levels of applied water could be defined as optimal in one sense or another (English et al., 1990):

- The level of applied water at which crop yields per unit of land are maximized;
- The level at which yields per unit of water are maximized;
- The level at which net income per unit of land is maximized;
- The level at which net income per unit of water is maximized.

The optimum level of applied water for a particular situation will be that which produces maximum profit or crop yield, per unit of land or per unit of water, depending on whether the goal is to maximize profits or food production and whether the most limiting resources is water or land. The two other levels of applied water are the deficit levels at which net returns will be equal to those which would be realized by full irrigation (English and Raja, 1996).

Irrigation management of crops involves a balance between vegetative and reproductive growth. Excessive vegetative growth can delay maturity and reduce final yield. One of the irrigation strategies that could be implemented to reduce excessive vegetative growth maintain yield and reduce water use, leading to an improvement in water use efficiency, is regulated deficit irrigation (RDI), which 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 most desirable benefits associated with implementing RDI strategy in crops are:

- The reduction in excessive vegetative growth
- Maintenance of soil moisture in the most agronomical desirable range
- An increase in water use efficiency, and
- The ability to better capture and use in-season rainfall events after an irrigation event due the maintained deficit.

Where water scarcity exists at regional level, irrigation managers should adopt the same approach to sustain regional crop production, and thereby maximize income (Stegman et al., 1990). Burt et al., (1997) defined irrigation efficiency (IE) as the proportion of irrigation water input to the farm for crop production that was used by the crop as evapotranspiration (ET) over the growing season. Tennakoon and Milroy (2003) defined crop water use efficiency (CWUE) as crop production per unit of ET. CWUE quantifies the efficiency with which economic yield is produced as a function of water used by the crop in the field. Furthermore, Tennakoon and Milroy (2003) defined farm water use efficiency (FWUE) as the amount of yield produced per millimeter of total seasonal water input at the farm level. Oad et al., (2001) calculated irrigation water use efficiency (IWUE) from the marketable fruit yields and amount of water applied to the plants. Moreover, they calculated total water use efficiency (TWUE) as the ratio of marketable fruit yields to water use.

The objectives of this study were to determine water use and yield in four annual crops with contrasting response to deficit irrigation (DI); corn, 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 annus 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 corn (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. Melody) was sown on 2 June 2003 and 10 June 2004 at a density of 8 plants m^{-2}.

For corn, crop evapotranspiration (ET) in both years was measured using a set of two drainage lysimeters of 4 m2 surface area (2 m × 2 m) by subtracting the volume of drainage from the irrigation amount. The lysimeters, 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 m² surface area (4 m × 4 m) 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. Water was supplied to the lysimeter when the weight loss reached a threshold value. Data were transferred via telephone modem to the irrigation laboratory, 500 m from the lysimeter. ET was determined as the difference between lysimeter weight gains (irrigation and/or rain or dew) and the lysimeter weight loss (from soil evaporation and plant transplantation) divided by the lysimeter surface area (16 m^2), so that day/night ET from midnight to midnight was computed as the average of 96 readings (one reading for each 15-minute time scale). The lysimeter has an ET accuracy and resolution of 1 kg, which corresponds to 0.062 mm of water for a surface area of the soil in the lysimeter. Water percolating through the soil mass of the lysimeter was collected and measured in a drainage reservoir located at the bottom of the lysimeter, so that drainage was accounted for in the water balance calculation of the lysimeter (Karam et al., 2005).

For cotton and sunflower, crop evapotranspiration (ET) was estimated using the FAO method (Doorendos and Pruit, 1977) by multiplying reference evapotranspiration (ETrye-grass) as measured in rye-grass lysimeters by the corresponding crop coefficients (Kc), which were derived for the different growth stages (Doorenbos and Kassam, 1988):

$$ET = ET_{rye\text{-}grass} \times K_c$$

Reference evapotranspiration (ETrye grass) was measured in a set of two rye-grass drainage lysimeters of 4 m² surface area (2 m × 2 m) 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.

Water was distributed in the field uniformly and simultaneously at 100% of field capacity using line source drippers, 16 mm in diameter, 40 m long, aligned W-E and spaced 70 cm apart. The dripper spacing was 40 cm, each delivering 4 l hr-1 of irrigation capacity at 100 kPa pressure.

For corn, deficit irrigation was applied continuously during the growing cycle upon the measured crop evapotranspiration (ET). Water was then applied at 100% (I-100 treatment) and 60% (I-60 treatment) of ET. For soybean, cotton and sunflower, deficit irrigations were made by cutting-out irrigation or for a two-week period during one or more of the different growth stages. For soybean, deficit irrigations were applied at full bloom (R2 stage), at seed enlargement (R5 stage) and at mature seeds (R7 stage). For cotton, deficit irrigations were applied at first open boll, at early boll loading, and at mid-boll loading. For sunflower, irrigation was withheld for a two-week period prior to flowering (E2 stage), at mid flowering (F1 stage), and at the beginning of seed formation (M0 stage) and at seed ripening (M2 stage). For all crops, a control was fully-irrigated throughout the growing period. Table 1 illustrates the deficit irrigation treatments for the crops under study.

At sowing, crops were irrigated to keep water content at 100% of soil available water. Weeds and insects were adequately controlled. Each species was grown in a different section in a 2-ha contiguous experimental field. Irrigation treatments were laid out within each crop in a block design with three or four replications.

In the plots, evapotranspiration was calculated using a simple soil water balance model (Doorenbos and Kassam 1988):

$$ET = I + P - D_r - R_f \pm \Delta_s$$

Where ET is evapotranspiration, I is irrigation application, P is effective rainfall, Dr is drainage water, Rf is amount of runoff, and Δs is change in the soil moisture content determined by gravimetric sampling. All terms in this equation are expressed in mm.

Moisture content in the 0-90 cm soil profile was measured gravimetrically before irrigations. Since there was no observed runoff during the experiment and the water table was at 4 m depth, capillary flow to the root-zone and runoff flow were assumed to be negligible in the calculation of ET. Drainage below 90 cm, after a number of soil-water content measurements, was considered as negligible. So the above equation was reduced to:

$$ET = I + P \pm \Delta_s$$

Soil moisture in the plots was also measured using a Sentry 200-AP TDR (Time Domain Reflectometry). The TDR was calibrated to the soil at Tal Amara over a wide range of soil moistures (Sentry, 200-AP, 1994). Four access PVC tubes, 50 mm in diameter and 1.0 m in length, were inserted in the middle rows of each plot. Readings were taken one day before irrigation and 2-to-3 days after irrigation during the growing seasons at 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm of the soil profile. Readings were then converted to soil moisture content values using a locally-calibrated equation. Gravimetric measurements and TDR readings were used to estimate seasonal ET in the plots using a water balance model as indicated above.

At physiological maturity, all individual plants in the sampling areas were harvested to determine above ground biomass production (B) and yield (Y). For corn, grain number per m2 and the 1000-grain weight were determined. For soybean and sunflower, seed number per m2 and the 1000-seed weight were also determined. For cotton, yield was determined by weighting lint at dry basis in the sampling areas.

Our study is largely based on the linear relationships between Y and B in one hand, and ET in the other hand. For this reason, we fitted linear models to the data:

$$Y = a1\,(ET) + b1$$

$$B = a2\,(ET) + b2$$

These models are the simplest and more often used models to describe the relationships between yield, biomass and evapotranspiration. These relationships are appropriate frameworks to investigate the pattern of water use efficiency, i.e. WUE = YET-1, or WUE = BET-1. This concept is widely used in agronomic research. Departure from linearity can be tested through regression of log Y or log B on log ET (Thompson et al., 1991). However, as this test can produce misleading results when the y-intercept differs from zero, polynomial regressions were preferred, as in Thompson et al. (1991).

In corn, soybean and sunflower, water use efficiency at grain or seed-basis (WUEg,s) was calculated as the ratio of yield at dry basis to the amount of crop evapotranspiration (Y/ET), while water use efficiency at biomass-basis (WUEb) was calculated as the ratio of biomass at dry basis to ET (B/ET) (Foroud et al., 1993; Howell et al., 1998). In cotton, water use efficiency at lint-basis (WUEl) was calculated as dry lint yield to the amount of water evapotranspired from the crop (Tennakoon and Milroy, 2003). WUE was expressed in kg m-3 (1 kg m^{-3} = 1 g m^{-2} mm^{-1}).

Table 1: Deficit-irrigation treatments of the various crops under study.

Crop	Period	Treatment	Period of irrigation cutout
Corn	1998	I-100	No irrigation restriction during the growing period
		I-60	Deficit irrigation at 6-leaf stage (from d.o.y 164 to d.o.y 255)
	1999	I-100	No irrigation restriction during the growing period
		I-60	Deficit irrigation at 6-leaf stage (from d.o.y 170 to d.o.y 250)
Soybean	2000	C	No irrigation restriction during the growing period
		S-1	Irrigation cutout at full bloom (R2 stage) (from d.o.y 215 to d.o.y 227)
		S-2	Irrigation cutout at seed enlargement (R5 stage) (from d.o.y 236 to d.o.y 250)
		S-3	Irrigation cutout at mature seeds (R7 stage) (from d.o.y 250 to d.o.y 264)
	2001	C	No irrigation restriction during the growing period
		S-1	Irrigation cutout at full bloom (R2 stage) (from d.o.y 197 to d.o.y 211)
		S-2	Irrigation cutout at seed enlargement (R5 stage) (from d.o.y 218 to d.o.y 232)
		S-3	Irrigation cutout at mature seeds (R7 stage) (from d.o.y 232 to d.o.y 246)
Cotton	2001	C	No irrigation restriction during the growing period
		S-1	Irrigation cutout at first open boll (from d.o.y 217 to d.o.y 259)
		S-2	Irrigation cutout at early boll loading (from d.o.y 231 to d.o.y 259)
		S-3	Irrigation cutout at mid boll loading (from d.o.y 245 to d.o.y 259)
	2002	C	No irrigation restriction during the growing period
		S-1	Irrigation cutout at first open boll (from d.o.y 232 to d.o.y 274)
		S-2	Irrigation cutout at early boll loading (from d.o.y 246 to d.o.y 274)
		S-3	Irrigation cutout at mid boll loading (from d.o.y 260 to d.o.y 274)
Sunflower	2003	C	No irrigation restriction during the growing period
		S-1	Irrigation cutout prior to flowering stage (from d.o.y 232 to d.o.y 274)
		S-2	Irrigation cutout at mid flowering stage (from d.o.y 246 to d.o.y 274)
		S-3	Irrigation cutout at the beginning of seed formation (from d.o.y 260 to d.o.y 274)
		S-4	Irrigation cutout at mid seed ripening (from d.o.y 260 to d.o.y 274)
	2004	C	No irrigation restriction during the growing period
		S-1	Irrigation cutout prior to flowering stage (from d.o.y 232 to d.o.y 274)
		S-2	Irrigation cutout at mid flowering stage (from d.o.y 246 to d.o.y 274)
		S-3	Irrigation cutout at the beginning of seed formation (from d.o.y 260 to d.o.y 274)
		S-4	Irrigation cutout at mid seed ripening (from d.o.y 260 to d.o.y 274)

RESULTS AND DISCUSSION

Evapotranspiration, yield and water use efficiency

Table 2 shows the values of evapotranspiration (ET), yield (Y), biomass (B) and water use efficiency of the various crops under well and deficit irrigation conditions.

Corn

Seasonal ET reached on the drainage lysimeter amounts of 952 mm and 920 mm in 1998 and 1999, for total growing cycles of 128 days and 120 days, respectively. In the plots, crop evapotranspiration totaled in the well-irrigated treatment (I-100) 863 mm and 833 mm in 1998 and 1999, respectively, while in deficit-irrigated treatment (I-60) ET totaled 575 mm and 556 mm in 1998 and 1999, respectively (Karam et al., 2003).

Grain yield on a dry basis declined in 1998 from 1520 gm-2 on the lysimeter to 1450 gm^{-2} on the full irrigated treatment (I-100) to 1080 gm^{-2} on the deficit-irrigation treatment (I-60). In 1999 these reductions ranged from 1340 gm^{-2} on the lysimeter to 1280 gm^{-2} and 1040 gm^{-2} on I-100 and I-60, respectively. Total aboveground biomass at harvest was also reduced by deficit irrigation. In 1998, a reduction of 130 gm^{-2} was observed in I-100 in comparison with the lysimeter, while the reduction on I-60 exceeded 800 gm^{-2} when compared to I-100. In 1999, these reductions were 100 gm^{-2} and 400 gm^{-2}, respectively.

Grain-related water use efficiency (WUEg) of lysimeter grown corn was 1.52 kg m^{-3} in 1998 and 1.34 kg m^{-3} in 1999. However, fully-irrigated corn had a WUEg of 1.68 kg m^{-3} in 1998 and 1.54 kg m^{-3} in 1999. Higher WUEg 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 (WUEb) 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.

Soybean

Total evapotranspiration (ET) as measured by the drainage lysimeters in 2000 totaled 800 mm for a total growing period of 140 days. However, when ET was measured by the weighing lysimeter in 2001, it was 725 mm during a growing period of 138 days (Karam et al., 2005).

Average seed yield was 3.2 t ha^{-1} in the control treatment, compared to 3.5 t ha^{-1} in the lysimeter, whereas total aboveground biomass productions were 7.3 t ha^{-1} and 8.1 t ha^{-1}, respectively. Deficit irrigation during R2 stage (S1) reduced biomass production by 16% ($P<0.01$) with comparison to the control (C). Deficit irrigation at R5 stage has resulted in significant reductions ($P<0.01$) of 28% of seed yield in the S2 treatment, while the reduction in aboveground biomass was only 6%, with respect to the control, while deficit irrigation at R7 stage (S3) reduced only by 6% ($P<0.05$) seed yield in the S3 treatment.

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

Cotton

Lysimeter measured crop evapotranspiration (ET) totaled 641.5 mm in 2001, while when estimated with the FAO method in 2002 it averaged 669.0 for total growing periods of 134 days in 2001 and 140 days in 2002.

Average across years, the highest lint yield was obtained in S1 treatment, where it amounted 638.7 kg ha^{-1}, followed by S2 (576.9 kg ha^{-1}) and S3 (546.7 kg ha^{-1}), while the control produced the lowest yield (457.0 kg ha^{-1}).

The highest lint water use efficiency (WUEl) was encountered 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, WUEb 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.

Table 2: Crop evapotranspiration (ET), yield, biomass and water use efficiency at grain or seed basis ($WUE_{g,s}$) and water use efficiency at biomass basis (WUE_b) of the various treatments

Crop	Variety	Period	Treatment	ET (mm)	Yield* (t/ha)	Biomass (t/ha)	WUE_y* (kg m^{-3})	WUE_b* (kg m^{-3})
Corn	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	827.0	4.96	21.05	6.00	25.45
			S-1	676.0	5.43	25.25	8.03	37.35
			S-2	664.0	5.59	24.64	8.42	37.11
			S-3	686.0	5.16	22.59	7.52	32.93
			S-4	726.0	5.31	21.10	7.31	29.06
	Arena	2004	Lysimeter	-	-	-	-	-
			C	827.0	5.60	32.35	6.77	39.12
			S-1	676.0	5.82	37.22	8.61	55.06
			S-2	664.0	5.83	39.43	8.78	59.38
			S-3	686.0	5.81	37.61	8.47	54.83
			S-4	726.0	5.43	31.68	7.48	43.64

Sunflower

Year-to-year sunflower evapotranspiration reached a total of 827 mm, as calculated from the FAO method. Average seed yield averaged in the full-irrigated control was 4.96 t ha^{-1}. Deficit irrigation increased seed yield by 9.5% in S1 treatment, 12.7% in S2 treatment, 4.0% in S3 treatment and 7.0% in S4 treatment, with comparison to the control. Moreover, average seed-related water use efficiency (WUEs) of the fully-irrigated control an average of 0.60 kg.m^{-3}, while WUEs values of the deficit-irrigation treatments were 0.80, 0.84, and 0.75 kg m^{-3}, in S1, S2, S3 and S4, respectively.

Relationships of yield, biomass and evapotranspiration

Corn

The yield of field-grown corn tended to increase linearly with ET from a range of 500-600 mm (I-60 treatment) up to about 800-900 mm (I-100 treatment). Beyond these values, in the range of ET between 900 and 1000 mm, additional water consumption did not increase significantly yield, as marked in Figure 1. As a result, the slope of yield response curve to ET of corn was relatively constant up to 800-900 mm, and then it decreased for ET values higher than 900 mm. The average slope was equal to 10.5 kg ha^{-1} mm-1. However, the coefficient of correlation was relatively high (R2 = 0.88). At biomass-basis, the slope of the response curve of biomass versus ET was equal to 22.2 kg ha^{-1} mm^{-1}, and the coefficient of correlation was 0.64.

Soybean

A linear relationship between seed yield and ET, with a weak but positive slope, was found in soybean plants (Figure 2). This weak correlation indicates that soybean can compensate the effects of early water stresses, as described earlier in this paper. Moreover, the coefficient of correlation was also found to be very low (R2 = 0.05). In the range of ET variation between 500 and 800 mm, the slope of the response curve of seed yield versus ET was 1.6 kg ha^{-1} mm^{-1} for seed yield and 6.2 kg ha^{-1} mm^{-1} for aboveground biomass.

Cotton

Excessive irrigation application in cotton promotes vegetative growth at the expense of reproductive development and lint yield. This was observed in Figure 3, where lint yield decreased with increased ET in the range of 500-600 mm. Negative linear regression relationship was found between cotton yield and evapotranspiration. The slope of the regression curve was -1.6 kg ha^{-1} mm^{-1}, however, high coefficient of correlation was observed (R2 = 0.87). Deficit irrigation at first open boll (S1 treatment) caused greater yield increase than at early boll development (S2 treatment) and mid-boll development (S3 treatment). Deficit irrigation at first open boll seemed to limit vegetative growth and led to a good fruit set and higher yields.

Sunflower

Figure 4 shows that seed yield of sunflower decreased with increased ET in the range of variation of 500-900 mm. Negative linear regression relationship was found between seed yield and biomass in one hand, and evapotranspiration in the second hand. The slopes of the regression curves was -3.4 kg ha^{-1} mm^{-1} for yield versus ET (R2 = 0.46) and -35.8 kg ha^{-1} mm^{-1} for biomass versus ET. Deficit irrigation at the beginning of seed formation (S3 treatment) and at mid seed ripening (S4 treatment) caused greater yield increase than at flowering stages (S1 and S2 treatments), and consequently WUE values were higher in the former treatments than the later treatments.

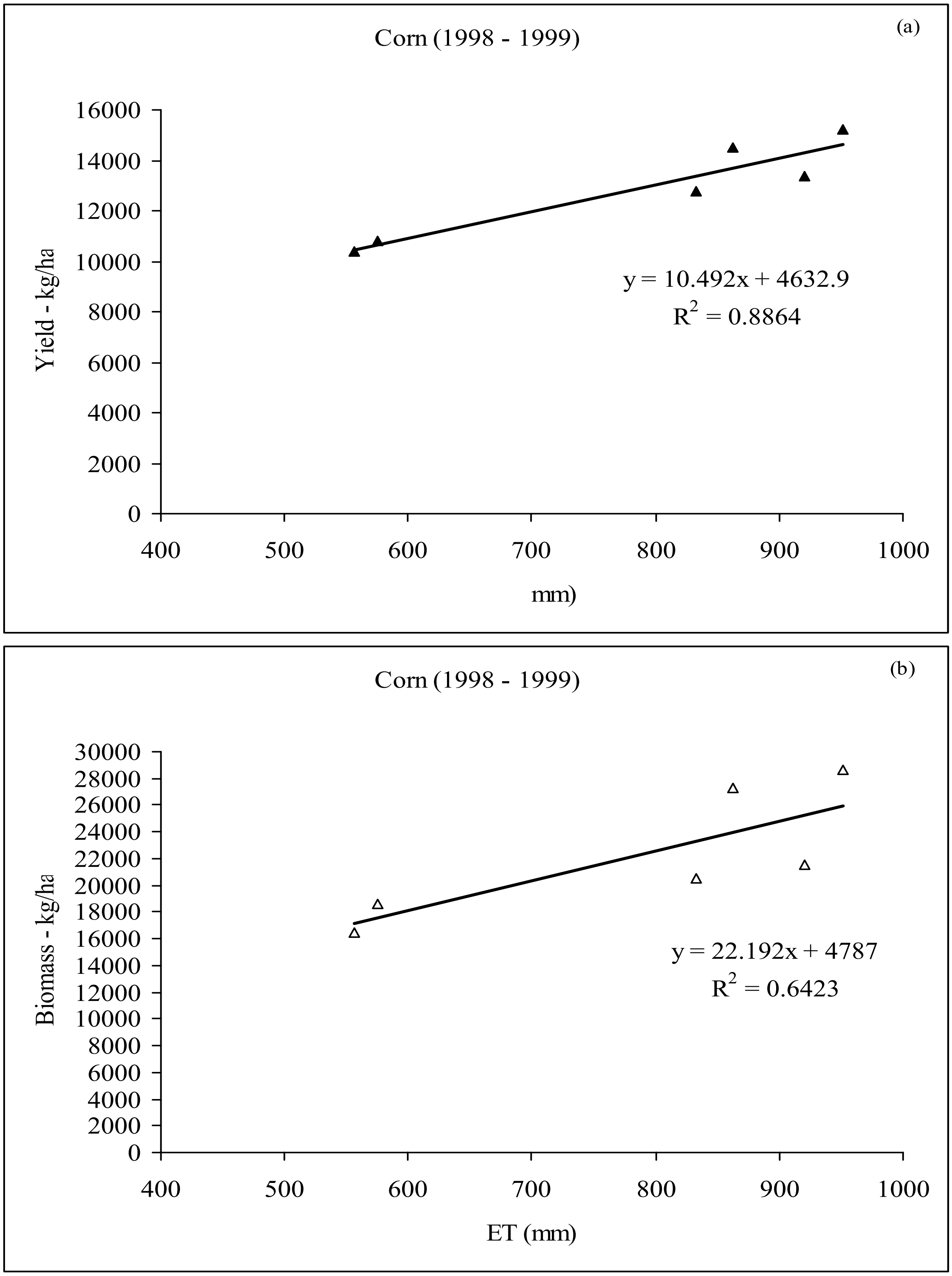

Fig. 1. Relationship between yield (a) and biomass (b) and evapotranspiration of corn (data points are means of five quadrates of $1m^2$ each per treatment ± 1 S.E; The lines represent linear regression trend lines)

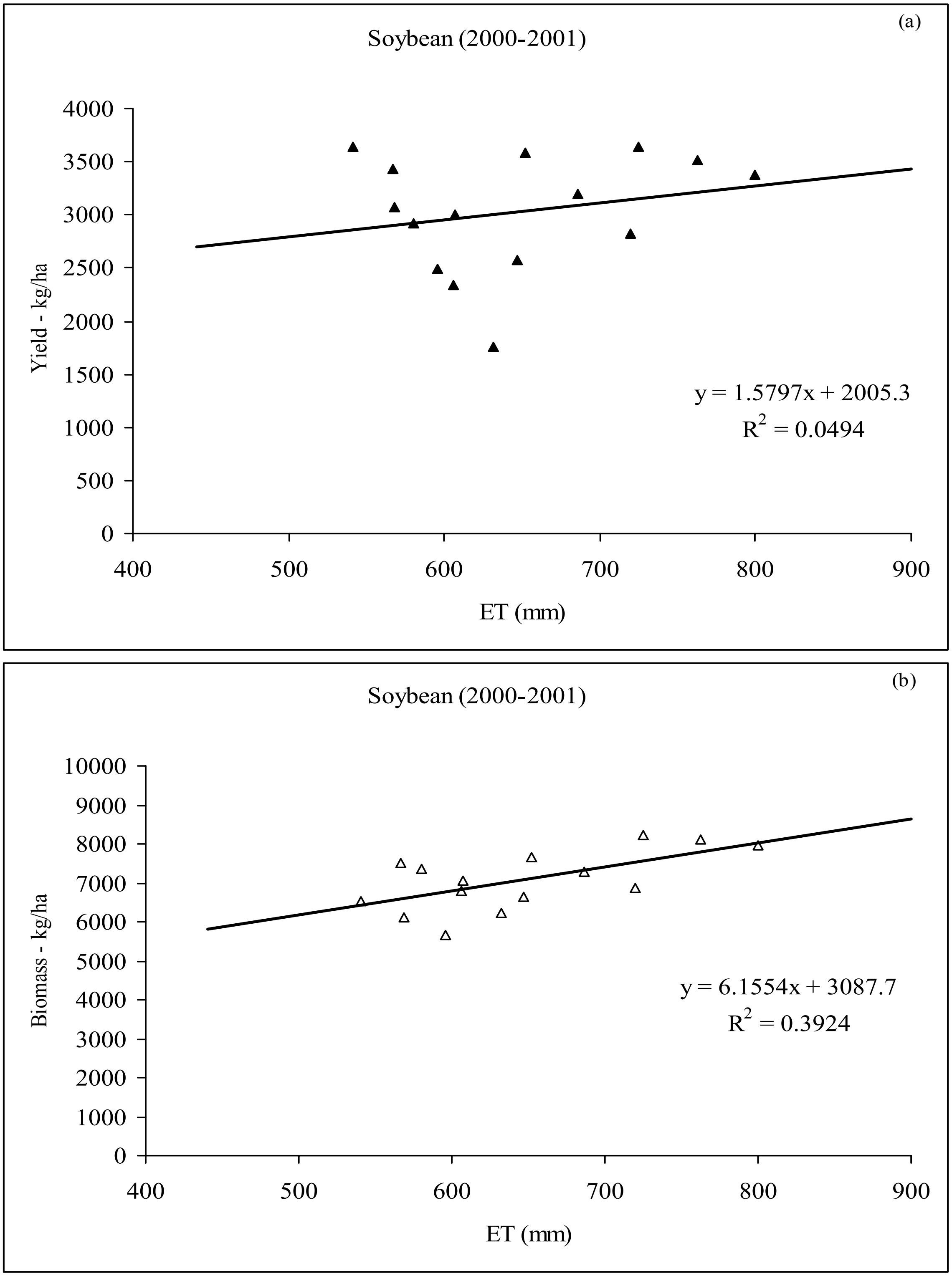

Fig. 2. Relationship between yield (a) and biomass (b) and evapotranspiration of soybean (data points are means of five quadrates of $1m^2$ each per treatment ± 1 S.E; The lines represent linear regression trend lines)

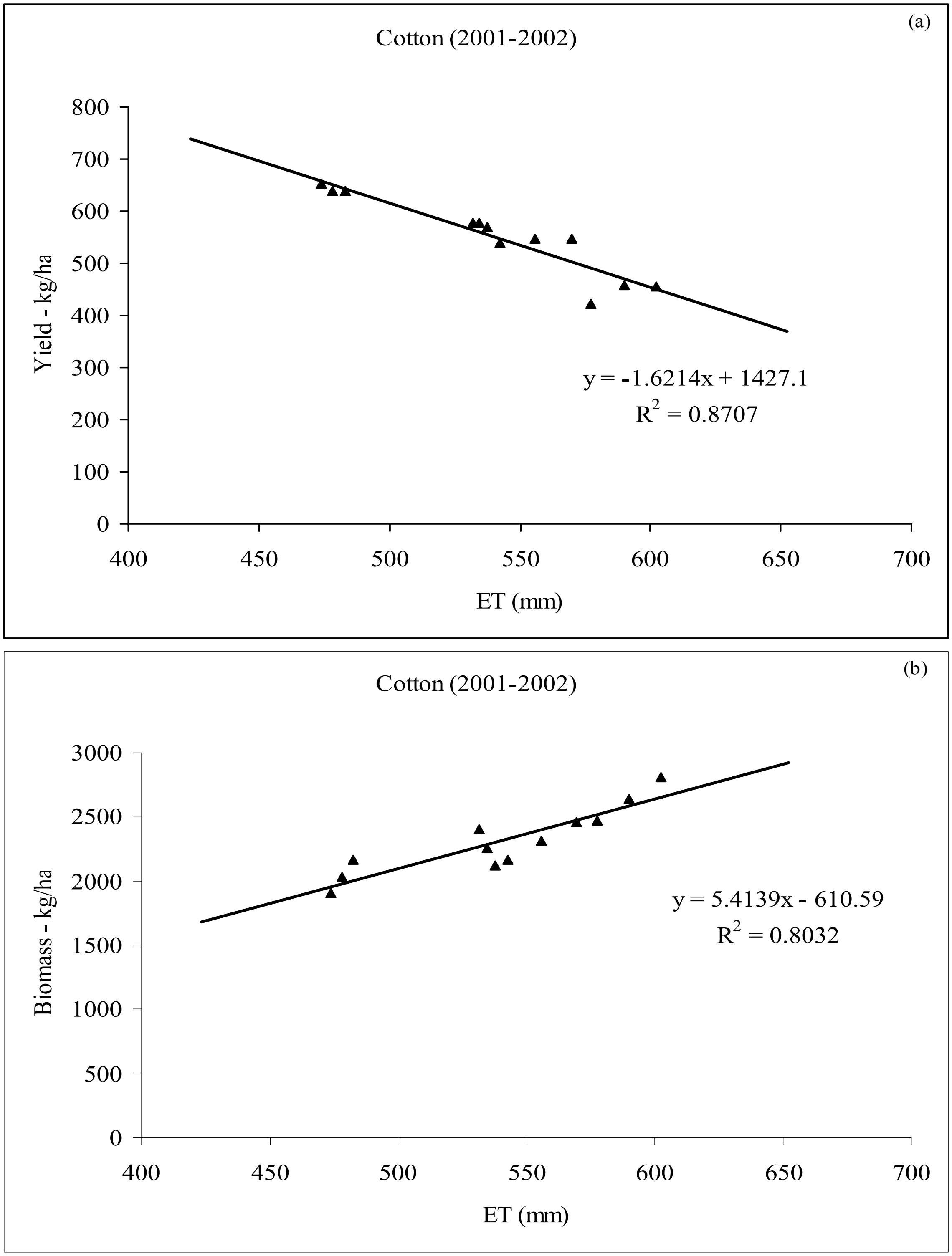

Fig. 3. Relationship between yield (a) and biomass (b) and evapotranspiration of cotton (data points are means of five quadrates of $1m^2$ each per treatment ± 1 S.E; The lines represent linear regression trend lines)

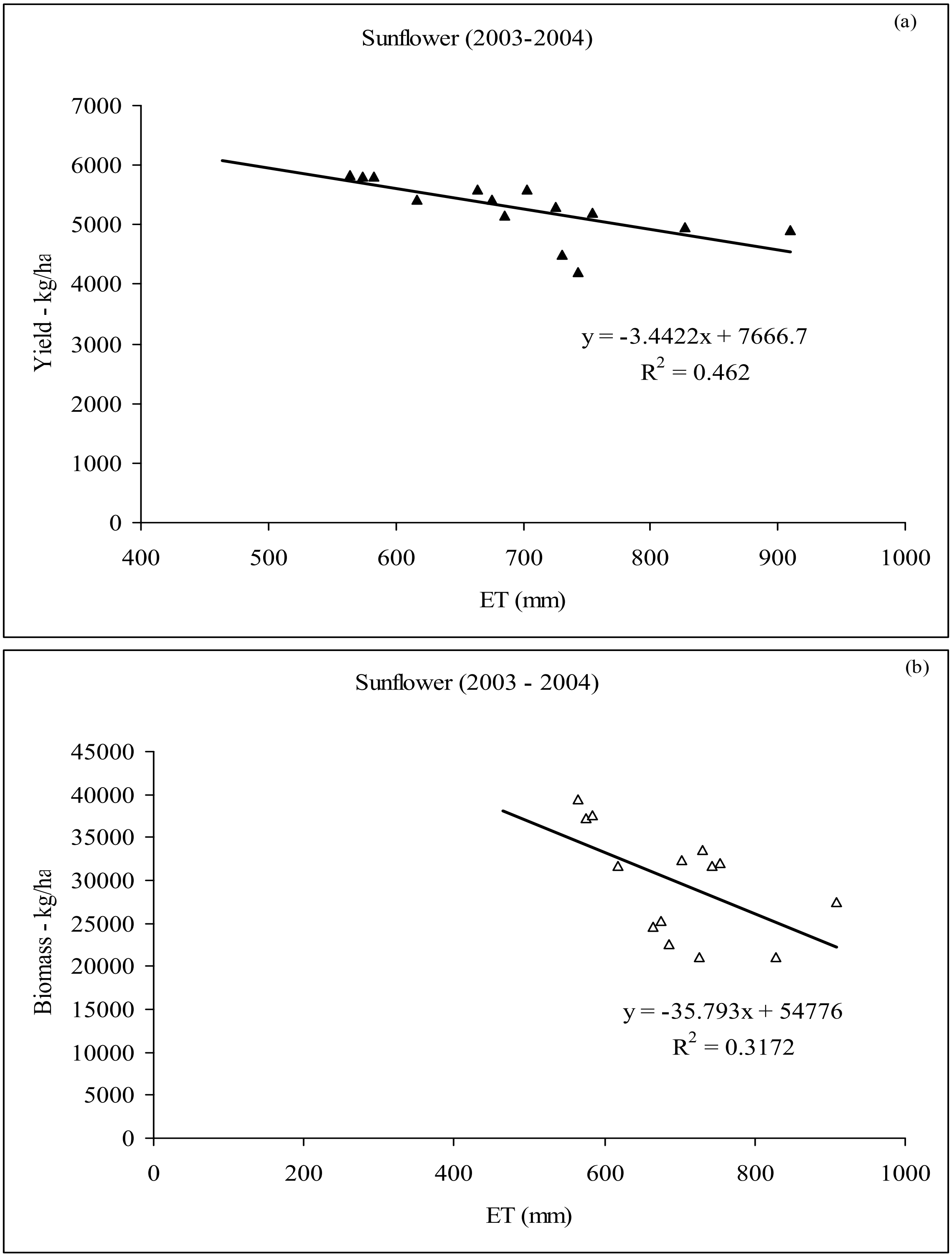

Fig. 4. Relationship between yield (a) and biomass (b) and evapotranspiration of sunflower (data points are means of five quadrates of 1m^2 each per treatment ± 1 S.E; The lines represent linear regression trend lines)

CONCLUSIONS

Clearly, water use efficiency is not only dependent on the total water applied but also when it is applied. Given that maximum yield was observed at a given ET value, WUE shows a general decline above this value. Therefore, an optimum seasonal ET varying between 500 and 900 mm was indicated for each crop, where the highest yield was observed. This provides high yield potential with maximum WUE, and may provide a useful guide for retrospectively assessing irrigation strategy.

The relationship between yield and ET is an appropriate framework to investigate the pattern of 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. Thus, our study was largely based on the relationships between Y and ET. Additionally, we investigated the relationship between biomass and ET.

The linear models are the simplest and more often used models to describe the relationship between Y and B, in one hand and ET, in the second hand. Departure from linearity can be tested through regression of log Y on log ET, or log B on log ET. However, as this test can produce misleading results when the y-intercept differs from zero, polynomial regressions were preferred, as in Thompson at al. (1991). Moreover, these two models have important implications for the water use efficiency, either at grain or seed basis, or biomass basis. Depending on whether the slope is constant or variable, and whether the intercept is zero or negative, the expected relationship between Y and B and ET can be outlined.

It is worthwhile noting that the parameters a1 and a2 were positives in corn and soybean, with intercepts b1 and b2 different from zero, indicating thus the relationships between Y and B and ET were positively correlated. However, the coefficient of correlation was much higher in both relationships for corn than for soybean. These results demonstrate that corn has a limited capacity to adjust grain yield in response to water availability, while soybean can compensate the effects of early water stresses. On the contrary, the parameters a1 and a2 were negatives in cotton and sunflower, with intercepts b1 and b2 different from zero, indicating thus the relationships between Y and B and ET were negatively correlated. However, the coefficient of correlation was much higher in cotton than in sunflower.

Maximum WUE values at grain basis were close to 1.88 kg m^{-3} in corn, 0.55 kg m^{-3} in soybean, 0.64 kg m^{-3} in cotton, 0.62 kg m^{-3} in sunflower. Our study demonstrated that WUE stability strongly varied among deficit irrigation treatments of the same species.

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