Pak. J. Bot., 42(4): 2541-2550, 2010.

LOWER AND UPPER BASELINES FOR CROP WATER STRESS INDEX AND YIELD OF *GOSSYPIUM HIRSUTUM* L. UNDER VARIABLE IRRIGATION REGIMES IN IRRIGATED SEMIARID ENVIRONMENT

M. USMAN[1*], M. ARSHAD[1], A. AHMAD[2], N. AHMAD[1], M. ZIA-UL-HAQ[3], A. WAJID[2], T. KHALIQ[2], W. NASEEM[2], Z. HASNAIN, H. ALI[3] AND S. AHMAD[3*]

[1]Department of Irrigation and Drainage, [2]Agro-Climatology Laboratory, University of Agriculture, Faisalabad- 38040, Pakistan
[3]Department of Agronomy & Chemistry, Bahauddin Zakariya University, Multan-60800, Pakistan
[*]Corresponding author E-mail: shakeel.agronomy@googlemail.com

Abstract

Cotton (*Gossypium hirsutum* L.) is an important cash crop of Pakistan. The study regarding determination of lower and upper base lines for crop water stress index (CWSI) for cotton was conducted during summer, 2006 at Post Agricultural Research Station, University of Agriculture, Faisalabad situated at latitude 31°25′N, longitude 73°09′E and altitude 184.4 m from sea level. Experiment comprised of five treatments of irrigation levels replicated thrice under randomized complete block design. Vapor pressure deficit (VPD) was also measured for this purpose. Upper baseline was established by growing a separate treatment T_5 without any irrigation or excessive rainfall. While lower baseline was established by using air and canopy temperature attained on clear sunny days within 5-8 days of irrigation and rainfall application. Effect of treatments on leaf area index (LAI) was observed and a relationship was established between yield and LAI. The relationship between yield and seasonal mean CWSI was found to be linear. No significant differences were found in yield of treatments T_3 and T_4, suggesting that an extra irrigation may be saved in treatment T_4 without any significant loss in yield. Water use efficiency (WUE) was found non significant among different irrigation treatments with overall mean value of 0.54 kg m^{-3}.

Introduction

Stability and growth of all the nations in the world is only possible by using their resources efficiently and effectively and it is imperative to increase the production of crop plants both in quality and quantity to meet the challenge of food security (Ahmad *et al*., 2008 & 2009a). Pakistan’s economy and agriculture is heavily dependent on the availability of water (Ahmad *et al*., 2009b). The competition of irrigation water for agriculture has increased in arid and semi-arid zones of Pakistan. Limited availability of irrigation water requires fundamental change in irrigation management and urges the application of water saving methods (Dagdelen *et al*., 2009). The irrigation water requirements must be assessed accurately and conserved to the maximum possible extent in order to meet the requirements of irrigated area as well as that of increasing population. Proper irrigation management requires that growers assess their irrigation needs by taking measurements of various physical parameters and prepare the answer of two questions “when to irrigate?” and “how much to apply?” There are several approaches to decide when to irrigate based on soil, such as feel method, gravimetric method, tensiometer, electric resistance blocks, neutron probe, and phene cells, based on atmospheric parameters and based on plant appearance and growth, leaf water potential, stomatal resistance and leaf temperature. Plant indicators enable the grower to use the plant directly for clues as to when to irrigate, not an indirect parameter, such as soil or evaporative demand. Observing plant characteristics can give a good idea for the status of the field's moisture content (Reddi & Reddy, 1995). Stanghellinil & Francesca (1994) evaluated the sensitivity of two different methods of water stress detection in a simulated patch of pasture grown in a greenhouse. The performance of two indices based on canopy temperature and soil water content. The soil water content based gauged the time domain reflectometry system, was assessed against actual evapotranspiration (ET), measured by accurate weighing system. Both methods were able to detect water shortage by the time transpiration was reduced to some 80% of its potential value. The soil-based index, however, relied on the estimate of root water extraction rate, which was unknown. It was concluded that detection of water shortage by means of a canopy temperature-based stress index was to be preferred to measuring soil water deficits by time domain reflectometry, despite the accuracy of the time domain reflectometry based soil water content estimate. The canopy temperature (T_C) provided an efficient method for rapid, non-destructive monitoring of whole plant response to water stress (Jackson *et al.,* 1981). They also stated that the behavior of T_C both under stress and non-stress conditions provided clues for crop water status. The CWSI, derived from canopy air temperature (T_A) difference versus the air vapor pressure deficit, was found to be a promising tool for quantifying CWSI (Jackson *et al.,* 1981; Idso & Reginato, 1982; Jackson, 1982). The CWSI calculations are based on three main environmental variables: T_C, T_A and atmospheric vapor pressure deficiency. All these three variables have much influence on water used by plants (Braunworth, 1989). Plant indicator is best because when partial or full stomatal closure occurs due to reduced transpiration because of reduced availability of water to the plant; there is rise in leaf temperature. Infrared thermometry can be used for rapid quantification of water stress in crop species by use of CWSI (Gardner *et al.,* 1992). A hand held infrared thermometry measures the difference between plant canopy and ambient temperature. The number of degrees by which canopy temperature exceeds air temperature each day or accumulated until a certain level is reached. A level, which depends on the crop and soil, is predetermined and when this level is reached it is time to irrigate. Irrigation water availability is a major concern in cotton production during hot and dry summer periods of the year. Frangmeier *et al*., (1989) planted an experiment on cotton. Water application rates were about 0.6' 1.0, and 1.3 times estimated consumptive use. Significant differences in seasonal average crop water stress values, average soil water contents, and yields were obtained for three water treatments. The wettest treatment with average CWSI values near 0.1 gave the highest yield and had the highest soil water contents before irrigation. The yield increased nearly with decreasing CWSI while, the WUE (water use efficiency; yield per unit of water) was highest for the 1.0 CU treatments. Dagdelen *et al*., (2006) studied the effect of different irrigation regimes on crop yield, yield response and WUEs. The average seasonal water use values ranged from 257 to 867 mm in cotton. Water deficit significantly affected the yield. The average yield of seed cotton varied from 1780 kg ha^{-1} to 5490 kg ha^{-1}. The average WUE varied from 0.61 kg m^{-3} to 0.72 kg m^{-3}, while average irrigation water use efficiency ranged from 0.77 kg m^{-3} to 1.40 kg m^{-3}. Keeping all in view, the main objectives of the study were (I) to develop upper and lower baseline for determination of CWSI. (ii) to assess the impact of different irrigation regimes on cotton yield and WUE under irrigated semiarid environment.

Materials and Methods

Study area: The study was carried out at the Post Graduate Agriculture Research Station, University of Agriculture, Faisalabad, Pakistan (Latitude 31°25′N, longitude 73°09′E and altitude 184.4 m from sea level). The area falls in the rice-wheat and sugarcane-wheat agro-ecological zones of the Punjab province. The important summer crops of this region are maize (*Zea mays* L.), rice (*Oryza sativa* L.), cotton (*Gossypium hersutum* L.), sugarcane (*Saccharum officinarum* L.) and pearl-millet (*Pennisetum americanum* L.). The winter crops are wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), gram (*Cicer arietinum* L.), berseen (*Trifolium alexdrinum* L.), rape seed & mustard (*Brassica spp*.). In the area, during the summer, the mean maximum and minimum temperature is 39 and 27°C, respectively and in winter 21 and 6°C, respectively. The soils of the study area are predominantly medium to moderately coarse with favorable permeability characteristics and show a similarity throughout the area. The soils are generally low in organic matter, with a pH in the range of 7 to 7.9. The soils are adoptable to wide variety of crops and having favorable internal drainage characteristics (Ahmad, 2002). The irrigation system in the area was originally designed for 65% cropping intensity. However, the cropping intensity has increased up to 160% in the last two to three decades, enabled by additional supplies from groundwater extraction. Both surface and groundwater is available for irrigation.

Design, treatments and crop husbandry: The experiment was laid out under randomized complete block design. The total experimental area was 0.174 ha. There were total 15 experimental plots for five treatments replicated three times. An individual treatment (T_5) was planted without any access to irrigation or rainfall. Individual plot size was 7.62 by 15.24 m. Watercourse was so laid that all the plots received direct irrigation from watercourse. The experiment comprised the following treatments i.e., T_0 = Non irrigated (only rainfall); T_1 = One irrigation at vegetative stage; T_2 = One irrigation at vegetative stage and one at flowering stage; T_3 = One irrigation at vegetation stage, one at flowering and one at boll formation stage; T_4 = One irrigation at vegetation, one at flowering, one at boll formation and one at late stage; T_5 = Controlled treatment (without rainfall or irrigation). Treated seeds of cotton (CIM-496) were sown with hand seed drill on the lines marked with marker on 174 day of year (DOY) in 2006. Two dozes of fertilizers were applied to the field. Full doze of Di-ammonium Phosphate (DAP) @ 115 kg ha^{-1} was applied uniformly to all plots at the time of sowing. Nitrogen as urea was applied in two splits. Half of the nitrogen @ 58 kg ha^{-1} was applied at time of sowing along with DAP, whereas the second doze @ 58 kg ha^{-1} was applied at the time of first irrigation. The irrigations were applied to field at different growth stages of crop for different treatments as mentioned in Table 1.

Canopy temperature: The canopy temperature was measured using a hand held infrared thermometer, equipped with 8-14 µm spectral band-pass filter. The Infrared thermometry collections were started on 202 day of year and continued until the 334 DOY during 2006. The canopy temperature was measured on 4 plants when fully sunlit, at a distance of 0.30 m to 0.50 m from the crop, with oblique measurements at 20^o to 30^o from the horizon to minimize soil background in the field of viewed and then averaged. Canopy temperature was measured on clear sky days at solar noon preferably between noon and 2:00 p.m. (Erdem, *et al.,* 2006) to assure that the measurements should been taken at maximum solar intensity. Plants transpire through little openings called stomata. Once plants go into water stress, they begin to close their stomata and cease to transpire, causing the plant to heat up and canopy temperature to rise. Infrared readings can detect this increase in plant temperature.

Table 1. Irrigation depth and schedule at various growing stages.

Irrigations	Irrigation date (DOY) in 2006	Growth stage	Irrigation regimes (cm)				
			T_0	T_1	T_2	T_3	T_4
1st	186	Vegetative	-	60	60	60	60
2nd	247	Flowering	-	-	60	60	60
3rd	278	Boll formation	-	-	-	60	60
4th	308	Late	-	-	-	-	60

DOY (Day of year)

Leaf area and leaf area index: Leaf area was measured at randomly selected plants from each treatment using leaf area meter (Licor, 3100) by taking an appropriate sub sample of green leaves (5 g) from each treatment. Total leaf area was measured by using the total weight of leaves. The leaf area index was calculated as the ratio of leaf area to ground area.

Vapor pressure deficit: The vapor pressure deficit is the difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated. The following relationship was used for the measurement of vapor pressure deficit; VPD = $e_a - e_d$
where; e_a= saturation vapor pressure [k Pa]; e_d = actual vapor pressure [k Pa]; e_a = 0.611 exp [17.27T/T+237.3]; T = air temperature (°C); $e_d = e_a (T_{WET}) - \gamma_{asp} (T_{DRY} - T_{WET}) P$; γ_{asp} = 0.00066 for Assmann aspiration at 5 m s^{-1} (C^{-1}) = 0.0008 for natural ventilation at 1 m s^{-1} (C^{-1}) = 0.0012 for indoor ventilation at 0 m s^{-1} (C^{-1}]; T_{DRY}: dry bulb temperature (°C); T_{WET}: wet bulb temperature (°C); P: atmospheric pressure [k Pa]; $e_a (T_{WET})$: saturation vapour pressure at wet bulb temperature [k Pa]; $P = 101.3[(293-.0065z)/293]^{5.26}$ and Z = elevation (m).

Crop water stress index: The crop water stress index (CWSI) values were calculated using the procedures of Idso *et al*., (1981a). In this approach, the measured crop canopy temperatures were scaled relative to minimum canopy temperature expected under non-water stressed conditions and the maximum temperature under severe water stress. The non-water stressed baseline for the $T_C - T_A$ versus the vapor pressure deficit relationship was determined using data collected from the well-watered treatment. The upper (fully stressed) base-line (UL) was computed according to the procedures explained by Idso *et al*., (1981a). Using the upper and lower baselines, crop water stress index (CWSI) was defined by scientists (Idso *et al*., 1981a):

$$CWSI= [(T_C - T_A) - (T_C - T_A)_{LL}] / [(T_C - T_A)_{UL} - (T_C - T_A)_{LL}]$$

where, LL (lower base-line) is the non-water stressed base line and UL (upper base-line) is the non-transpiring base line.

Estimation of water use efficiency: The water use efficiency (WUE) was calculated by following the procedure adopted by Ahmad *et al*., (2008).

Statistical analysis: The yield and WUE data were analyzed using PROC/GLM (General Linear Model) procedure of SAS institute (Anon., 1997). Significantly means were separated using LSD at 5% probability level.

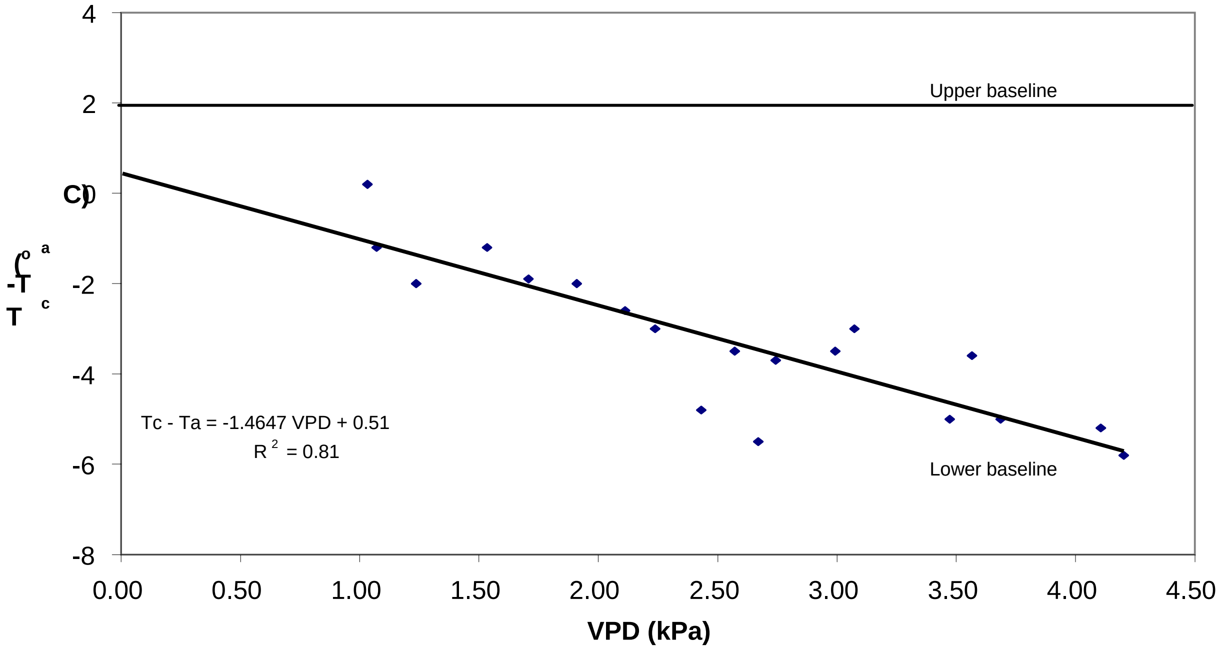

Fig. 1. Lower and upper base-lines for determination of CWSI.

Results and Discussions

Upper and lower base lines for CWSI determination: The lower (non-stressed) base-line and upper (stressed) base-lines (Fig. 1) were measured for cotton. The CWSI values were calculated using this diagram as the relative value between upper and lower base-lines relaying the difference between canopy and air temperatures to vapor pressure deficit (Idso *et al*., 1981b). The resulting base-line was described by the linear equation described in Fig, 1. This lower base-line for the same crop was different as described by different researchers. The climate, soil type and plant variety might cause difference in the intercept and slope of the base-line. The linear relationship between $T_C – T_A$ and vapor pressure deficit (VPD) was also found for cotton by Reginato (1983), $T_C – T_A$ =1.2 - 2.24 VPD. Development of lower base line at a single location was often limited by the VPD range that occurred, thereby limiting the base-line transportability to other locations (Gardner *et al.,* 1992). In this experiment, the lower base-line was developed for a wide range of VPD (1-4.3 k Pa). The upper base-line represents $T_C – T_A$ for the plants, which were severely stressed. The upper base-line was derived from the treatment T_5, as maximum difference between $T_C – T_A$ was observed in treatment T_0, which was not irrigated even a single time during the study period. When, canopy temperature difference taken on selected days at 12:00 to 14:00 hours from treatment 'T_0', drawn against VPD, the intercept of the line is 2°C, which is treated as maximum possible $T_C – T_A$ difference for this study. The base-line is drawn parallel to VPD from this point.

Leaf area index: The leaf area index (LAI) is the main physiological determinant of crop yield. The effects of different irrigation levels on LAI of cotton at different harvests are presented in (Fig. 2). Early in the season, 25 days after sowing (DAS), the leaf expansion was slow and could not intercept more radiation for all treatments with almost similar values of LAI for all the treatments. LAI measurements at 50 DAS, observed to be 0.56 for treatment T_1 and 0.63, 0.65, 0.66, 0.64, for treatments T_2, T_3, and T_4, respectively. This higher increase in LAI after 50 DAS would be due to application of first irrigation to all the treatments except 'T_o'. Moreover, the values of LAI measured for treatments T_1, T_2, T_3 and T_4 observed were almost similar. Afterwards LAI increased linearly with advancement of crop plant up to 75 DAS. The measurements of LAI after 100 DAS observed to be high for treatments T_2, T_3, T_4 with highest value of 2.68 for treatment T_4, while for treatment T_1, it was observed to be 2.29. This might be due to the application of second irrigation to all the treatments except treatments 'T_0' and T_1. The highest value of LAI measured to be 4.08 and 4.0 for treatments T_4 and T_3, respectively after 125 DAS. This increased value of LAI in treatments T_3 and T_4 might be due to third irrigation application (only to treatments T_3 and T_4). LAI values decreased with the decrease in irrigation turns for all the treatments (Fig. 2). It was concluded that water stress cause a decrease in LAI and reduction of yield (Turner *et al.,* 1986). The peak value of LAI of cotton was 4.1 in the study of Orgaz *et al*., (1992). The relationship between LAI and seed yield of cotton was positive and common regression accounted for 96.3 % variability in the seasonal data (Fig. 3).

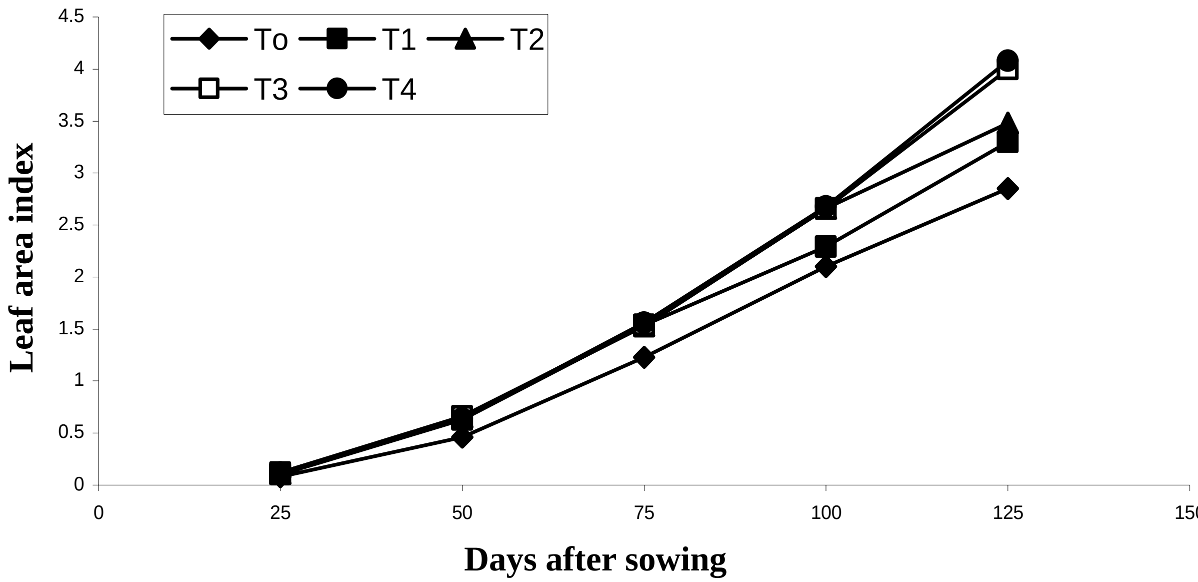

Fig. 2. Leaf area index (LAI) for five treatments after 25, 50, 75, 100, and 125 days of sowing.

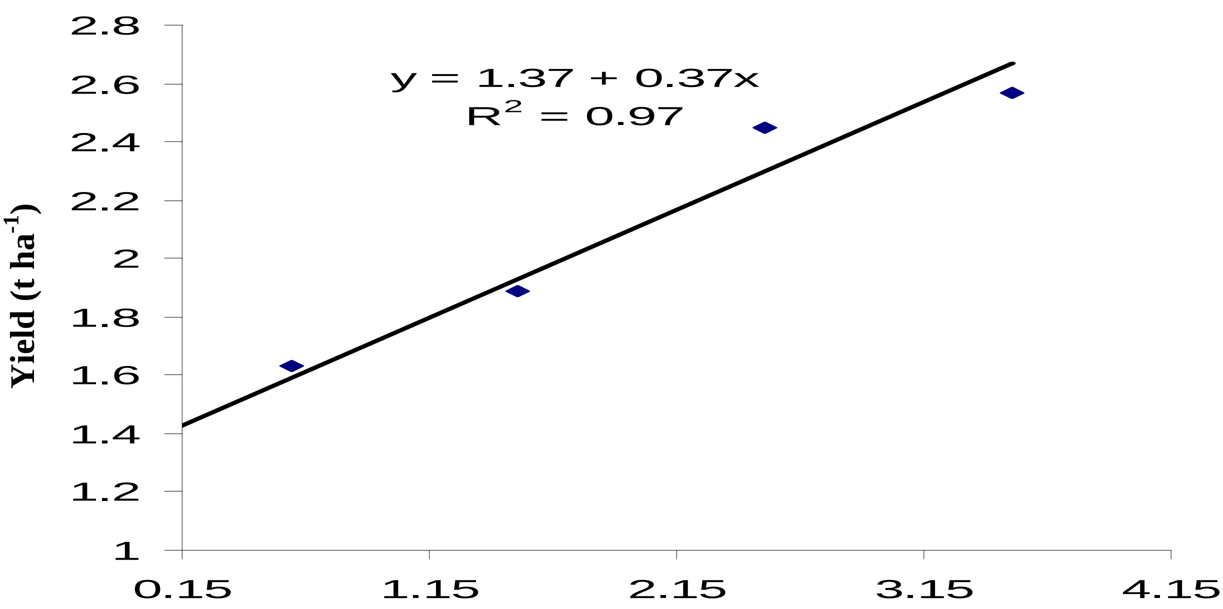

Fig. 3. Relationship between LAI and seed yield of cotton

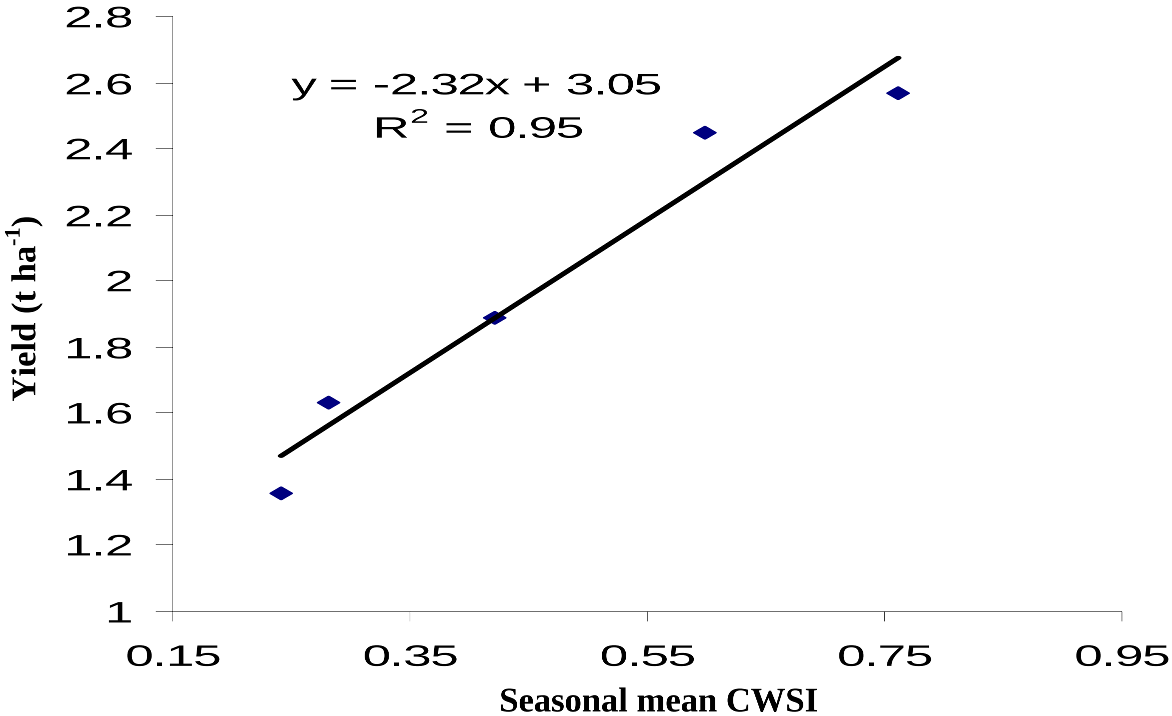

Fig. 4. Relationship between seed cotton yield and seasonal mean CWSI.

Table 2. Effect of treatments on seed cotton yield.

Variables	Seed cotton yield ($t\ ha^{-1}$)	Relative yield reduction (%)	WUE ($kg\ m^{-3}$)
T_0 (No irrigation)	1.36^{d*}	47.08	0.55^a
T_1 (One irrigations)	1.63^c	36.46	0.53^a
T_2 (Two irrigations)	1.89^b	26.34	0.52^a
T_3 (Three irrigations)	2.45^a	4.67	0.57^a
T_4 (Four irrigations)	2.57^a	0.00	0.53^a

***** Means followed by the same letter are not significantly different at 5% probability level.

Table 3. Comparison of present study for WUE values with others.

Source	Irrigation System	WUE ($kg\ m^{-3}$)
Present study	Flat Sowing	0.52-0.57
Hodgson *et al*., (1992)	Drip	0.22
Sezgin *et al*., (2001)	Drip	0.67-0.81
Yazar *et al*., (2002)	Drip	0.50-0.74
Yazar *et al*., (2002)	Lepa	0.55-0.67
Dagdelen *et al*., (2006)	Furrow	0.61-0.72
Ibragimov *et al*., (2007)	Drip	0.63-0.88
Dagdelen *et al*., (2008)	Drip	0.77-0.96

WUE (Water use efficiency)

Seed cotton yield: The data collected regarding seed cotton yield during the course of experimentation are given in Table 2. First, second, third and fourth irrigations were applied at vegetation, flowering, boll formation and at late stage of the crop, respectively. The analysis of variance indicated that different treatments affected the seed cotton yield significantly at 5% probability level. The higher seed cotton yield was T_4 (2.57 t ha^{-1}), while the treatment 'T_0' gave the lowest as compared to the other treatments. There was significant difference between treatment 'T_0' (1.36 t ha^{-1}) and T_1 (1.63 t ha^{-1}) at 5% probability level. In treatment 'T_0', there was no irrigation applied throughout the growing season of cotton except the climatic variations (rainfall etc.). The mean CWSI observed during the season was 0.76 in treatment 'T_0', while, in treatment T_1, irrigation was applied after 22 days of sowing. The treatment T_1 showed mean seasonal CWSI of 0.60, which is less than 'T_0' and this lead to significance difference in seed cotton yield between treatments 'T_0' and T_1. Treatment T_1 (1.63 t ha^{-1}) was significantly different with treatment T_2 (1893 t ha^{-1}) at 5% probability level (Table 2). The yield of treatment T_2 (1.89 t ha^{-1}) increased from treatment T_1 (1.63 t ha^{-1}). In treatment T_2, two irrigations were applied to the crop, one at vegetative and second at flowering stage, as compared to one in case of treatment T_1 at vegetative stage. The increase in the seed cotton yield of treatment T_2 might be due to the second irrigation applied at flowering stage, which is sensitive stage of crop for water use. Furthermore, this second irrigation also decreased mean CWSI in treatment T_2 (CWSI = 0.42) as compared to treatment T_1 (CWSI = 0.60). There was significant difference between treatments T_3 (2.45 t ha^{-1}) and T_2 (1.89 t ha^{-1}) at 5% probability level. The seed cotton yield of treatment T_3 (2.45 t ha^{-1}) was higher than that of treatment T_2 (1.89 t ha^{-1}). In treatment T_3, three irrigations were applied to the crop, one after 22 DAS at vegetative stage, second after 61 days of first irrigation at flowering stage, and third after 31 days of second irrigation at boll formation stage. The results indicated that if irrigation was not applied at boll formation stage, it might produce lesser seed cotton yield up to greater extent. Furthermore, third irrigation at boll formation decreased the mean CWSI value in treatment T_3 (CWSI = 0.28) as compared to T_2 (CWSI = 0.42). This indicated that due to availability of water to the crop at boll formation stage decreased the stress of the plants due to evapotranspiration (ET) effect, resultantly increase in seed cotton yield. There was no significant difference between treatment T_3 (2.45 t ha^{-1}) and treatment T_4 (2.57 t ha^{-1}) at 5% probability level. In treatment T_4, four irrigations were applied, one after 22 DAS, second after 61 days of first irrigation at flowering stage, third after 31 days of second irrigation at boll formation stage and fourth after 21 days of third irrigation at late stage. The reason for non-significance in seed cotton yield between treatments T_4 and T_3 indicated that fourth irrigation in treatment T_4 did not affect the seed cotton yield significantly. This might be that the fruiting stage was complete after third irrigation and fourth irrigation did not affect the boll formation. So, there was no significant difference in seed cotton yield between treatments T_3 and T_4. Furthermore, treatment T_4 (CWSI = 0.24) did not show a considerable difference in mean seasonal CWSI as compared to treatment T_3 (CWSI = 0.28). It was concluded that if third irrigation would not be applied at boll formation stage as in treatment T_3 (2.45 t ha^{-1}), it might lead to a considerable loss in seed cotton yield as in treatment T_2 (1.89 t ha^{-1}). The seasonal means for each treatment and seed cotton yield were plotted (Fig. 4). The relationship between seed cotton yield and seasonal mean CWSI values was negative linear and regression accounted for 0.96% variability in the seasonal data. This relation can be used to predict the yield potential of cotton. The average WUE of cotton crop during this study varied from 0.52 to 0.57 kg m^{-3} (Table 2). WUE for the treatment T_3 was found highest, while for T_2 it was the lowest. However, the differences between the treatments were non-significant at 5% probability level. The values were different than those of other researchers in different regions (Table 2). The comparison of the WUE values is also mentioned in Table 3.

Conclusions

The lower baseline is shown by the equation $T_C - T_A = -1.4647$ VPD + 0.51. The relationship between leaf area index and seed yield was found to be positive and can be represented by the relation; [Y = 973.98 LAI - 1429.7]. The relationship between mean seasonal crop water stress index and yield was primarily linear. This relationship can be used to predict the yield potential of cotton. As the treatment T_4 (2.57 t ha^{-1}) did not show wide difference in yield with treatment T_3 (2.40 t ha^{-1}), so it is recommended that fourth irrigation is not necessary for the crop.

Acknowledgements

The authors acknowledge the co-operation of the in-charge and field staff of Post Graduate Agriculture Research Station, University of Agriculture, Faisalabad, for conducting of this experimental trial. The authors also acknowledge the work of scientists cited in this paper and references there in.

References

Ahmad, I. 2002. *Water and New Technologies*. Global change impact studies centre (GCISC), Islamabad. Pakistan.

Ahmad, S., A. Ahmad, M. Zia-ul-Haq, H. Ali, T. Khaliq, M.A. Anjum, M.A. Khan, A. Hussain and G. Hoogenboom. 2009b. Resources use efficiency of field grown transplanted rice (*Oryza sativa* L.) under irrigated semiarid environment. *J. Food Agri. & Environ.*, 7(2):487-492.

Ahmad, S., M. Zia-ul-Haq, H. Ali, A. Ahmad, M. A. Khan, T. Khaliq, Z. Husnain, A. Hussain and G. Hoogenboom. 2009a. Morphological and quality parameters of *Oryza sativa* L. as affected by population dynamics, nitrogen fertilization and irrigation regimes. *Pak. J. Bot.,* 41(3):1259-1269).

Ahmad, S., M. Zia-ul-Haq, H. Ali, S.A. Shad, A. Ahmad, M. Maqsood, M.B. Khan, S. Mehmood and A. Hussain. 2008. Water and radiation use efficiencies of transplanted rice (*Oryza sativa* L.) at different plant densities and irrigation regimes under semi-arid environment. *Pak. J. Bot.,* 40(1):199-209.

Braunworth, Jr., W.S. 1989. The possible use of the crop water stress index as an indicator of evapotranspiration deficits and yield reductions in sweet corn. *J. Amer. Soc. Hort. Sci.*, 114:542-546.

Dagdalen, N., E. Yilmaz, F. Sezgin and T. Gurbuz. 2006. Water yield relation and water use efficiency of cotton (*Gossypium hirsutum* L.) and second crop corn (*Zea mays* L.) in Western Turkey. *Agri. Water Man.*, 82:63-85.

Dagdelen, N., H. Basal, E. Yilmaz, T. Gurbuz and S. Akcay. 2009. Different drip irrigations regimes effect cotton yield, water use-efficiency and fiber quality in Western Turkey. *Agri. Water Man.*, 96: 111-120.

Erdem, Y., S. Sezen, T. Erdem and D. Kenar. 2006. Determination of crop water stress index for irrigation scheduling of bean (*Phaseolus vulgaris* L.). *Turk. J. Gric.*, 30:195-202.

Frangmeier, D.D., D.J. Garrot, S.H. Husman and J. Perez. 1989. Cotton water stress under trickle irrigation. *Tran. ASAE*, 32(6): 1955-1959.

Gardner, R.B., D.C. Nielsen and C.C. Shock. 1992. Infrared thermometry and the crop water stress index. II. Sampling procedures and interpretation. *Prod. Agri.*, 5: 466-475.

Hodgson, A.S., G.A. Constable, G.R. Duddy and I.G. Danieles. 1992. A comparison of drip and furrow-irrigated cotton on a cracking clay soil. *Soil Fer.*, 55: 2.

Howell, T.A., J.L. Hatfield, H. Yamada and K.R. Davis. 1984. Evaluation of cotton canopy temperature to detect crop water stress. *Trans. ASAE*, 27(1): 84-88.

Ibragimov, N., S.R. Evett, Y. Esanbekov, B.S. Kamilov, L. Mirzaev and J.P.A. Lamers. 2007. Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. *Agri. Water Man.*, 90: 112-120.

Idso, S.B. and R.J. Reginato. 1982. Soil and atmosphere-induced plant water stress in cotton as infrared from foliage temperatures. *Water Resources Res.*, 18:1143-1148.

Idso, S.B., R.D. Jackson, P.J. Pinter, R.J. Reginato and J.L. Hatfield. 1981a. Normalizing the stress-degree-day parameter for environmental variability. *Agri. Meteor.*, 24: 45-55.

Idso, S.B., R.J. Reginato, R.D. Jackson and P.J. Pinter, Jr. 1981b. Measuring yield reducing plant water potential depressions in wheat by infrared thermometry. *Irri. Sci.*, 2: 205-212.

Jackson, R.D. 1982. Canopy Temperature and Crop Water Stress. In: *Advances in Irrigation*. (Ed.): D. Hillel. Academic Press, NY. p. 43-85.

Jackson, R.D., S.B. Idso, R.J. Reginato and P.J. Pinter. 1981. Canopy temperature as a crop water stress indicator. *Water Resources Res.*, 7: 1133-1138.

Orgaz, F., L. Mateos and E. Fereres. 1992. Agro-climatology and modeling: Season length and cultivar determine the optimum evapotranspiration deficit in cotton. *Agronomy J.,* 84: 700-706.

Reddie, G.H.S. and T.Y. Reddy. 1995. *Efficient use of irrigation water*. Kalyani Publishers, Ludhiana-14100, ISBN-272-0258-4.

Reginato, R.J. 1983. Field quantification of crop water stress. *Trans. ASAE*, 26(3): 772-781.

Anonymous. 1997. User's Guide: Statistics. Cary, NY: SAS Institute.

Sezgin, F., E. Yilmaz, N. Dagdelen and S. Bas. 2001. Effect of different irrigation methods and water supply level application on water-yield relations in cotton growing. *Third National Hydrology Congress, Univ. of Izmir, Turkey*, June 27-9.

Stanghellinil, C. and D.L. Francesca. 1994. A comparison of soil- and canopy temperature-based methods for the early detection of water stress in a simulated patch of pasture. *Springer Berlin / Heidelberg*, 14: 141-146.

Turner, N.C., A.B. Hearn, J.E. Begg and G.A. Constable. 1986. Cotton (*Gossypium hirsutum* L.) physiological and morphological responses to water deficits and their relationship to yield. *Field Crops Res.*, 14: 153-170.

Yazar, A., S.M. Sezen and S. Sesveren. 2002. LEPA and trickle irrigation of cotton in the southeast Anatolia project (GAP) area in Turkey. *Agri. Water Man.*, 54: 189-203.

(Received for publication 18 June 2009)