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Effect of water stress at different development stages on vegetative and reproductive growth of corn

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Abstract

A field study was carried out from 1995 to 1997 in order to determine the effect of irrigation and water stress imposed at different development stages on vegetative growth, grain yield and other yield components of corn (*Zea mays* L.). The field trials were conducted on a silty loam Entisol soil, with Pioneer 3377 corn hybrid. A randomised complete block design with three replications was used. Four known growth stages of the plant were considered and a total of 16 (including rain fed) irrigation treatments were applied. The effect of irrigation or water stress at any stage of development on plant height, leaf area index, grain yield per hectare, as well number of ears per plant, grain yield per cob and 1000 kernels weight, were evaluated. Results of this 3-year study show that all vegetative and yield parameters were significantly affected by water shortage in the soil profile due to omitted irrigation during the sensitive tasselling and cob formation stages. Water stress occurring during vegetative and tasselling stages reduced plant height, as well as leaf area development. Short-duration water deficits during the rapid vegetative growth period caused 28–32% loss of final dry matter weight. Highest yields were observed in the fully irrigated control (VTCM) and the treatment which allowed water stress during the vegetative growth stage (TCM). Even a single irrigation omission during one of the sensitive growth stages, caused up to 40% grain yield losses during dry years such as 1996. Much greater losses of 66–93% could be expected as a result of prolonged water stress during tasselling and ear formation stages. Seasonal irrigation water amounts required for non-stressed production varied by year from 390 to 575 mm. Yield response factor (k_y) values (unitless parameter) relating yield loss to water deficits) obtained for the first, second and third experimental years were determined to be 1.22, 1.36 and 0.81, respectively.

Keywords: Irrigation; Corn; Water stress; Growth; LAI; Grain yield; Yield response factor (k_y)

1. Introduction

Corn grain yields up to 15 t ha^{-1} can be obtained under irrigated conditions in the Thrace region in north-west Turkey, while yields of 5 t ha^{-1} are considered good in rain fed agriculture. Recently there has been interest in optimising irrigation application due to water scarcity in the region. The cost of irrigation pumping and inadequate irrigation scheme capacity as well as limited water sources are among the reasons that force many farmers to reduce irrigation applications. The fact that water stress effects on growth and yield are species- and variety-dependent is well known. Moreover, sensitivity to drought varies by development stage (Doorenbos and Kassam, 1979). Moisture stress

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occurring during different development stages of corn may reduce final grain yield to different degrees, and the extent of yield reduction depends not only on the severity of the stress, but also on the stage of the plant development (Wilson, 1968; Claasen and Shaw, 1970).

NeSmith and Ritchie (1992) have evaluated short- and long-term responses of corn to a pre-anthesis water deficit under prevailing soil and climatic conditions at Kalamazoo, MI. Short-term effects of water deficits are described as delaying leaf tip emergence and leaf area reduction. Long-term consequences are reported as reduced final sizes of the leaves and internodes and yield losses of 15–25%. Ritchie et al. (1992) reported that at about the V_{10} (10 visible leaves) stage the corn plant begins a rapid, steady increase in nutrient and dry weight accumulation, which continues into the reproductive stage. They concluded that water stress at this stage may limit the size of the leaves (the photosynthetic factory). Salvador and Pearce (1995) stated that though the corn plant life cycle consists of two clearly distinct independent (vegetative and reproductive) phases, vegetative structures such as stems and roots continue to grow after pollen shed and fertilisation have taken place, provided surplus nutrient assimilate is available.

Jama and Ottman (1993) have studied the effect of moisture stress during early growth stages of a corn plant including anthesis and found out that a delay in the irrigation during this stage decreased plant dry weight. In an experiment conducted under conditions of Bushland, TX, Yazar et al. (1999) evaluated the effect of six different irrigation levels on LEPA technique irrigated corn stress stature and grain yield. The authors reported that highest grain yield, dry matter, kernel numbers and water use efficiency were obtained from both the fully irrigated treatment and that receiving 80% of the required irrigation water amount applied.

Doorenbos and Kassam (1979) have reported that corn appears to be relatively tolerant to water deficits during the vegetative and ripening periods, and that the greatest decrease in grain yields is caused by moisture deficit in the soil profile during the flowering period. In field studies to evaluate the effect of deficit irrigation and nitrogen levels on the biomass yield, it was determined that severe water stress leads to less leaf area, lower crop growth rate, plant height, shoot dry matter and a 52% grain yield decrease over a range of nitrogen levels. It was concluded that optimization of inputs at the farm level would maximise biomass production as well as increasing the harvest index (Pandey et al., 2000a,b).

Several studies on the mechanisms that lead to grain yield decreasing under water stress have been conducted recently. Zinselmeier et al. (1999) subjected corn in buckets to conditions of low water potential (Ψ_w) for 5 days around pollination and observed that embryos formed but abortion occurred and kernel number decreased markedly. They observed also that all of the intermediates in starch synthesis were depleted and the starch contained in the ovary almost disappeared during this abortion. In a similar study, Setter et al. (2001) evaluated the processes of kernel setting under 5 days water stress and shading at the pre-pollination and early post-pollination stages and determined that both water and light deprivation, at both stages, decreased kernel set primarily in apical ear regions. Bolanos et al. (1993) found that few plant traits were correlated with the increase in yield under water deficit conditions observed through eight circles of selection in a tropical maize population. Of the many traits studied, including osmotic adjustment, only those factors associated with a delay in silking and barrenness were associated with a yield increase.

Knowledge about the sensitivity of corn plant to water stress during different growth stages has been widely used in studies aiming to develop deficit irrigation strategies, as well as to determine the yield response factor (k_y) of corn, a parameter used to quantify the effect of water stress, derived from the linear relationship between relative seasonal evapotranspiration deficits ($1-ET_a/ET_m$) and relative yield loss ($1-Y_a/Y_m$) (Musick and Dusek, 1980; Kanber et al., 1990; Ogretir, 1994; Yildirim and Kodal, 1998).

Stockle and James (1989) have analysed corn yields for full irrigation and four levels of deficit irrigation using a computer simulation model. Results indicated that slight deficits (ratios of actual to potential transpiration larger than 0.89) provided higher net benefit than full irrigation. Cavero et al. (2000) evaluated the ability of EPIC and CROPWAT models to simulate grain yield reduction due to water stress of different types (continuous or at given stages).

The purpose of the present study was to evaluate the response of maize growth and yield to water deficit in the soil profile during vegetative, tasselling, ear formation and milk stages, with a view to reducing irrigation applied with a minimum of yield loss.

2. Materials and methods

2.1. Experimental site and experimental procedure

Field experiments were conducted during 1995–1997 on fields of the Rural Services Research Institute in Kirklareli (41°42′N and 27°12′E). The experimental site has a silty loam Entisol soil (Udic Ustifluvent). That is poor (1.46–2.60%) in organic matter and rich in potassium. Values of some soil characteristics related to irrigation are presented in Table 1. Pioneer brand 3377 corn hybrid, the most popular in the research area, was over planted during the last week of April of each experimental year and thinned to a spacing of 0.7 m (row width) × 0.25 m. Nitrogen fertiliser at 140 kg N ha^{-1} was applied before sowing each year. Since the soil analysis results pointed out for the sufficient level of the phosphorus and potassium in the soil, no additional fertilisation was applied on the experimental site. Field trials were have been laid out in a randomised complete block design, with three replications. Each experimental plot was designed as 8.4 m wide × 4 m long (12 rows per plot) and had a total area of 33.60 m^2 at sowing. In order to prevent the lateral spread of water plots were surrounded with dikes and a distance of 3 m between plots was left bare. Furrows with uniform slope were formed in the experimental plots and used in the irrigation process. Field experiments were laid out on different locations across a larger field in each experimental year.

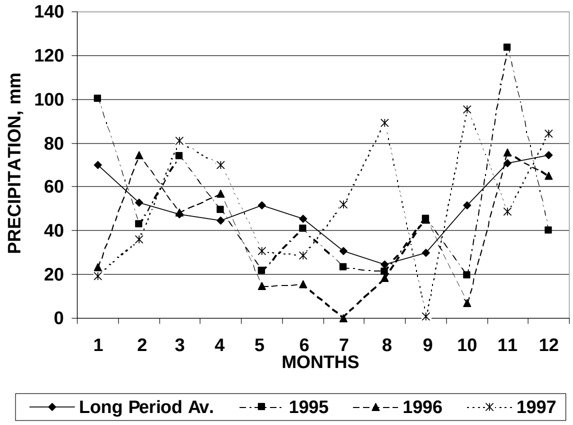

Fig. 1. Precipitation data summary for the corn experiment contrasted to 50-year averages (Anonymous, 1984).

2.2. Precipitation history

Daily weather climatic parameters were measured at a weather station located adjacent to the experimental site and precipitation amounts during the experimental years (1995–1997), as well as long-term averages are presented in Fig. 1, while data related to temperature and relative humidity for the growing period of the experimental years are summarised in Table 2. The years 1995 and 1997 were similar to the total yearly precipitation amount averages for a period of 50 years, but 1996 could be classified as very dry. The experimental years differed in terms of rate and distribution of the seasonal (vegetative) precipitation. The total monthly rainfall amounts during the periods of rapid vegetative growth, tasselling and ear

Table 1
Basic physical characteristics of the experimental soil

Depth (cm)	1995				1996				1997			
	FC (%)	WP (%)	BD (g/cm^3)	TG	FC (%)	WP (%)	Ag (g/cm^3)	TG	FC (%)	WP (%)	Ag (g/cm^3)	TG
0–30	20.3	8.1	1.41	SCL	21.9	10.8	1.46	SCL	18.8	9.4	1.46	SCL
30–60	22.2	9.3	1.40	SCL	21.3	10.9	1.44	SCL	18.3	9.6	1.55	SCL
60–90	18.7	8.5	1.42	SCL	17.5	9.1	1.49	SCL	18.5	9.7	1.55	SCL
90–120	19.5	8.8	1.43	SCL	18.8	9.5	1.45	SCL	19.6	10.9	1.53	CL

FC, field capacity; WP, wilting point; BD, bulk density; TG, textural description; SCL, sandy clay loam; CL, clay loam.

Table 2
Temperature and relative humidity data for the years and months of experiment

Month and meteorological event	May	June	July	August	September
1995					
Average temperature (°C)	15.8	22.3	23.4	22.0	18.2
Maximum temperature (°C)	28.6	32.8	32.2	32.4	30.2
Minimum temperature (°C)	1.0	11.2	13.2	12.0	6.5
Relative humidity (%)	64.1	57.2	56.3	56.0	61.7
1996					
Average temperature (°C)	19.2	21.8	24.2	22.7	17.4
Maximum temperature (°C)	30.6	34.8	37.8	34.6	29.4
Minimum temperature (°C)	9.0	10.0	12.5	13.8	7.0
Relative humidity (%)	56.5	41.4	37.4	43.4	51.3
1997					
Average temperature (°C)	17.6	21.8	23.4	20.6	16.0
Maximum temperature (°C)	34.0	33.2	36.0	33.2	29.4
Minimum temperature (°C)	6.2	7.5	12.4	12.2	6.2
Relative humidity (%)	53.2	52.8	45.1	57.8	57.9

formation stages (May–August) in the first experimental year (1995) were approximately equal to the long-term average rainfall of 152.3 mm. The second experimental year (1996) received a total of 49.1 mm in this same period. The last experimental year (1997) with the total of 200.8 mm precipitation recorded between May and August, was wet for the region.

2.3. Irrigation treatments and measurements

Four known corn growth stages, vegetative (V), tasselling (T), cob (ear) formation (C) and milk (M) stages of corn were identified, and a total of 16 irrigation treatments, including a non-irrigated (rain fed) treatment were applied (Table 3). Water application

Table 3
Irrigation treatments included in the study

Experimental treatments	Growth stages			
	Vegetative (V)	Tasselling (T)	Cob (ear) formation (C)	Milk stage (M)
VTCM	X	X	X	X
TCM	O	X	X	X
VTM	X	X	O	X
VCM	X	O	X	X
VT	X	X	O	O
VC	X	O	X	O
VM	X	O	O	X
TC	O	X	X	O
TM	O	X	O	X
CM	O	O	X	X
V	X	O	O	O
T	O	X	O	O
C	O	O	X	O
M	O	O	O	X
Rain fed	O	O	O	O

X, irrigated at a given stage; O, irrigation omitted.

Table 4
Irrigation water quantities applied to corn at different stages of the experimental years

Year and stage of development	Water application	Vegetative (V)	Tasselling (T)	Cob (ear) formation (C)	Milk stage (M)
1995	Application date[a]	36	64[b]/67[c]	79	88
	Irrigation water (mm)	90.8	152.2	156.8	125.0
1996	Application date[a]	38	65[b]/69[c]	75	89
	Irrigation water (mm)	107.4	181.8	147.1	138.0
1997	Application date[a]	40	66[b]/69[c]	75	85
	Irrigation water (mm)	57.0	151.1	92.5	86.3

[a] Days after emergence.
[b] Tasselling (days after emergence).
[c] Silking (days after emergence).

stages were determined according to Doorenbos and Kassam's (1979) approximation and vegetative and milk stages were precised as V6 and R3 (Ritchie et al., 1992).

All the experimental treatments were irrigated at the same time as the VTCM treatment, being watered at each growth period with the amount of irrigation water required to fill the 0–90 cm soil depth to field capacity. Individual treatments were treated similarly except for omitting the irrigation application at a specific growth stage. Water applied to each experimental plot was measured using a TEKSAN flowmeter connected to an irrigation pipe. The irrigation water amount applied to each experimental treatment to be irrigated at a given stage, as well as data concerning the application date are presented in Table 4. Soil moisture content of the plots was monitored (from sowing to harvest) for the layers of 0–30, 30–60, 60–90 and 90–120 cm with a neutron probe (CPN, 503 DR), using one access tube located at the centre of each plot. The neutron probe was calibrated using gravimetric soil analyses simultaneously with the neutron readings at all tubes over the experimental site before first irrigation application. A large number of readings and gravimetric samples have been taken for various depths and levels of moisture content, and strong ($P < 0.01$) linear relationships between moisture content and count ratios were derived for each experimental year.

Evapotranspiration (ET) from each plot was determined using the soil water balance equation: $\mathrm{ET} = P + I + R + \mathrm{SD} - D$, where P is the precipitation (mm), I the irrigation water amount (mm), R the runoff/runon (mm), SD the soil water depletion (mm), and D is the drainage (mm) below the root zone. Runoff/runon was considered zero because the experimental plots were surrounded with dikes. Soil water depletion was calculated as the difference between soil water content values at the beginning and end of each period for a soil depth of 1.2 m. Drainage below the root zone was assumed to be zero, since water applied with each irrigation was equal to water deficit in the 0–90 cm soil profile of the fully irrigated treatment (VTCM), and no water leaching below 1.2 m depth was observed from neutron measurements taken to a 1.5 m soil depth.

Plant height development was determined by measuring (from soil surface to growing tip before tasselling) five labelled plants for each plot prior to the first irrigation application, followed by weekly measurements. Three plants, from rows 2 to 11 of the 12-row plot, were cut at ground level, leaves were separated from the stem, and their shapes traced and area measured using a planimeter. Leaves were considered as one sample, and the rest of the plant as stalk, tassel, ear and shank (as the other sample), were cut into pieces, oven dried at 65 °C to a constant weight. The sum of dry weight of leaves and other parts was assumed to be the total dry matter (TDM) of the plant.

Grain was harvested from rows 4 to 9 of the 12-row plots using the centre 3.0 m of each row. After drying the ears under open-air conditions, the grains were manually removed from the cobs; weighed, and subsamples of approximately 0.25 kg per plot were weighed fresh, oven-dried to constant weight at 65 °C and re-weighed to determine the water content.

Grain yields were converted to a standard grain water content of 15%. The harvest data were analysed for ear number, grain yield per unit area, as well as for grain yield per ear, ear number per plant and 1000 kernel weight. A calculated estimate for kernels per ear for the plants with ears have been determined from data obtained from kernel and ear numbers per plot.

Data were subjected to an ANOVA using the procedure given by Yurtsever (1984), and the Duncan mean separation test procedure was applied. In order to compare the experimental years, data obtained for plant height and leaf area index (LAI) at their peak values at 70 days; yield and its components, and dry matter weight at 113 days after emergence, were subjected to an ANOVA test, and year × treatment interactions were evaluated. Regression was used to evaluate water use–yield relationships using seasonal evapotranspiration and grain yield data obtained from the experiment. Seasonal values of the yield response factor (k_y) for each experimental year was determined using the Stewart model (Stewart et al., 1977).

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y\left(1 - \frac{ET_a}{ET_m}\right) \quad (1)$$

where Y_a is the actual harvested yield (obtained from all the treatments), Y_m the maximum harvested yield (obtained from irrigated control), k_y the yield response factor, ET_a the actual evapotranspiration and ET_m is the maximum evapotranspiration.

3. Results and discussion

3.1. The effect of water stress on growth and biomass accumulation of corn

3.1.1. Plant height

Data concerning the effect of water stress on the vegetative growth of corn plant are plotted in Fig. 2. Irrigation applied at the beginning of two growth stages (vegetative and tasselling) affected plant height growth significantly ($P < 0.01$). Water application at the beginning of rapid growth increased the plant height of all the treatments receiving water at this time, and the effect was obvious as early as several days after the application. Additional water application just at the beginning of tasselling resulted in plant height up to 220 cm during the first experimental year. Plant height of the treatments exposed to water stress during the first growth stage, and those receiving their first irrigation on the onset of tasselling was dramatically increased after the water application and attained a height of 194 cm. Plants of the non-irrigated, C, M and CM treatments, exposed to additional

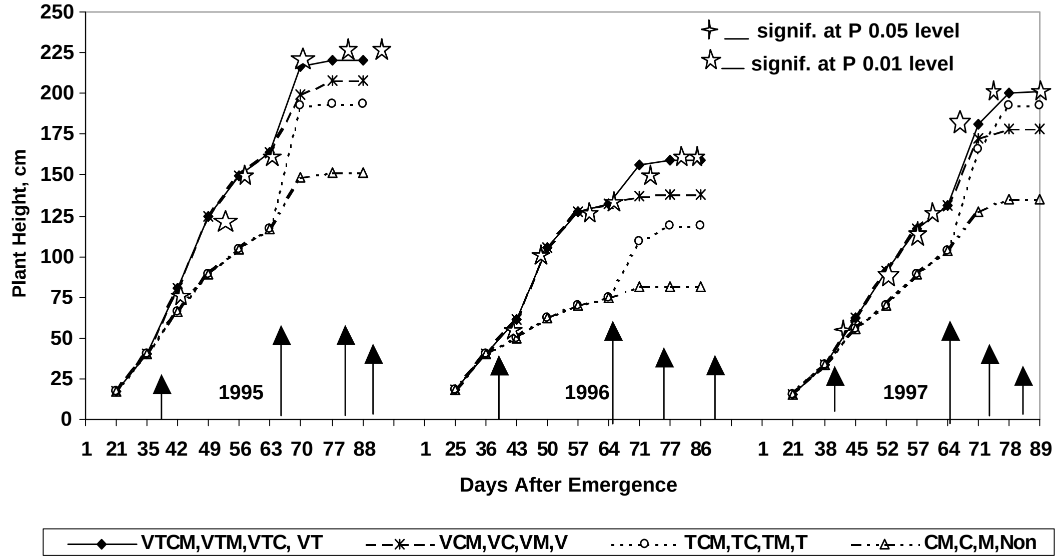

Fig. 2. Plant height growth pattern under water stress conditions at different stages (year × treatment interaction for peak values (70 or 71 days) is significant at $P < 0.01$ level). ↑ irrigation application.

water stress during the tasselling stage had the shortest final height of 152.1 cm.

Similar results have been obtained from observations carried out during the second and third experimental years, despite the severe drought experienced in 1996 dramatically decreased the growth of all treatment plants. Results obtained in 1996 contradict the widely held opinion in the literature that the corn plant is tolerant to moisture deficits during the vegetative stage, and support the claim of El Neomani et al. (1990) and Alam and Mahub-ul Alam (1985) that water stress during the rapid vegetative stage restricts plant growth. Effects of water deficits on plant height have been determined for other crops also. In experiments carried out in Texas, Pace et al. (1999) examined the response of cotton plants to a brief drought and subsequent recovery period and concluded that water deficits significantly deceased the plant height, stem diameter, number of the nods and dry weight of cotton plants.

3.1.2. Leaf area index

The effects of water deficit on green leaf number, dimensions and LAI were determined (Fig. 3). Results obtained from the 3-year study showed the significant effect ($P < 0.01$) of irrigation application or omission during any stage on LAI. As in the case of plant height, LAI development was very slow in the first part of the vegetative stage, followed by an intensive increase during tasselling and ear formation. Irrigation application 36 days after emergence (vegetative stage) increased the LAI value from 1.29 to 4.54 (measurements on day 56), while the value determined for treatments exposed to water stress during this stage was 3.29. Irrigation applied at the beginning of tasselling stage (64 days after emergence), made the differences between irrigated and stress treatments much more evident, since LAI increased to 5.44 and 4.16, respectively for watered and stressed plants.

In general, green leaf area index during the first experimental year under the adequate (VTCM) and well (VTC and TCM) irrigated treatments increased until 70–80 days after emergence, and then decreased as the older leaves died. LAI of the treatments with imposed water stress during the entire growth season (non-irrigated) or irrigated during the first and second growth stage and then left to stress during the rest of the season (V and VT) declined to zero as early as the day 114.

The severe drought experienced during 1996 and extraordinary high seasonal precipitation rates in 1997 contributed to some differences among the experimental years. Not only were maximum values of LAI for the adequate irrigated treatment in the dry year much lower (3.76–3.92), than those of the previous year (5.44–5.46), but also the LAI of almost all the

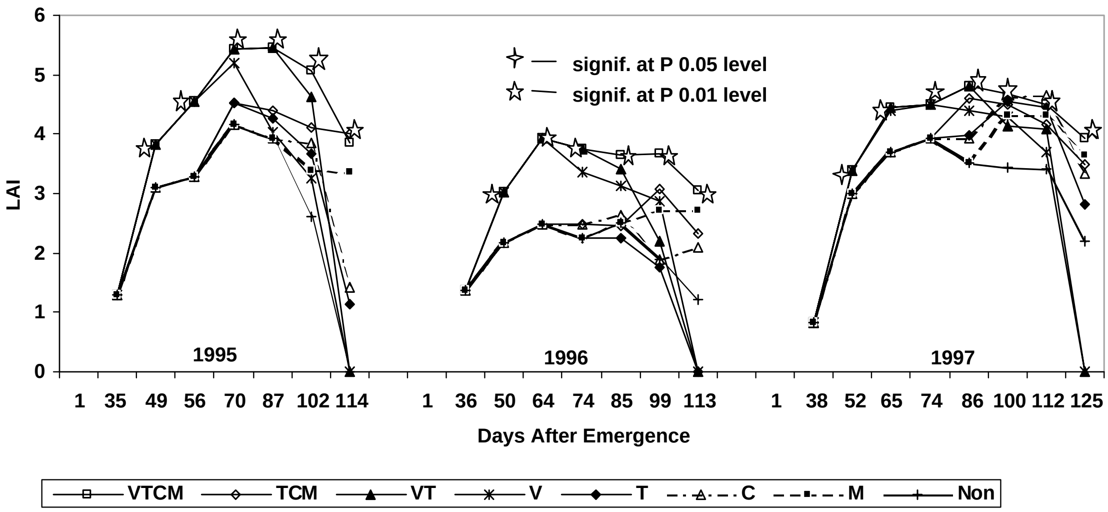

Fig. 3. Leaf area index (cm^2/cm^2) development of some treatments (year × treatment interaction for peak values of the years is significant at $P < 0.01$ level).

treatments with irrigation omission during the last (milk) stage declined to zero before 113 days. These differences between the years of experiment could be explained with lower precipitation rate accompanied with the effect of higher temperatures and lower relative humidity values in 1996 (Table 2).

Results concerning the effect of irrigation and water stress on leaf area and LAI, agree with the view that leaf elongation is among the plant processes most sensitive to water shortage (Hsiao, 1973). Values reported are comparable with leaf area values reported for two Pioneer hybrids by NeSmith and Ritchie (1992). On the other hand, the peak values of LAI, varying in the range of 4.5–5.5 under favourable moisture conditions, are similar to those measured and estimated using the CERES-LA model by Lizaso et al. (2003) at 60 days after planting for P3790 hybrid. The increase in LAI of the plants exposed to water stress at previous stages, and irrigated at tasselling or ear formation stages observed in our study, is a phenomena observed also in cotton (Pace et al., 1999). They reported that plants which are drought-treated at 36 days and rewatered at 49 days, still had lower height, fewer nodes and smaller stem dry weights than controls at the end of the recovery period (59 days after planting), while the leaf area of the drought treated plants appeared to be much closer to that of the non-stressed control. Istanbulluoglu et al. (2002) reported a positive linear relationship between the number of irrigations and LAI value.

3.1.3. Total dry matter accumulation

Total dry matter accumulation was also significantly affected by the soil water deficit (Fig. 4). Differences were significant at all measurement dates and experimental years. Even under favourable moisture conditions corn plants increased in weight slowly early in the growing season. As more leaves were exposed to sunlight, the rate of total dry matter accumulation gradually increases. In general, total dry matter accumulation was accelerated after each water application. Irrigation water applied at the beginning of the intensive vegetative growth stage accelerated the process of biomass accumulation. Under favourable moisture conditions of the VTCM treatment, the process of rapid dry matter accumulation continued until near harvest. The adverse effect of water stress on dry matter accumulation appeared to be significant under all water deficit levels, especially in the first and second experimental years. Even short-term water stress caused approximately 28 and 32% loss of final dry matter weight of the plants with omitted first irrigation (TCM), in 1995 and 1996, respectively, while no loss was observed during the rainy third experimental year. Serious decreases have been recorded for plants exposed to water stress during tasselling (VCM data not plotted) and those with omitted irrigation at ear formation (VTM not plotted) stages. Values of dry matter weight loss for these treatments were 25 and 15.7, and 19.2 and 11% during 1995 and 1996, respectively.

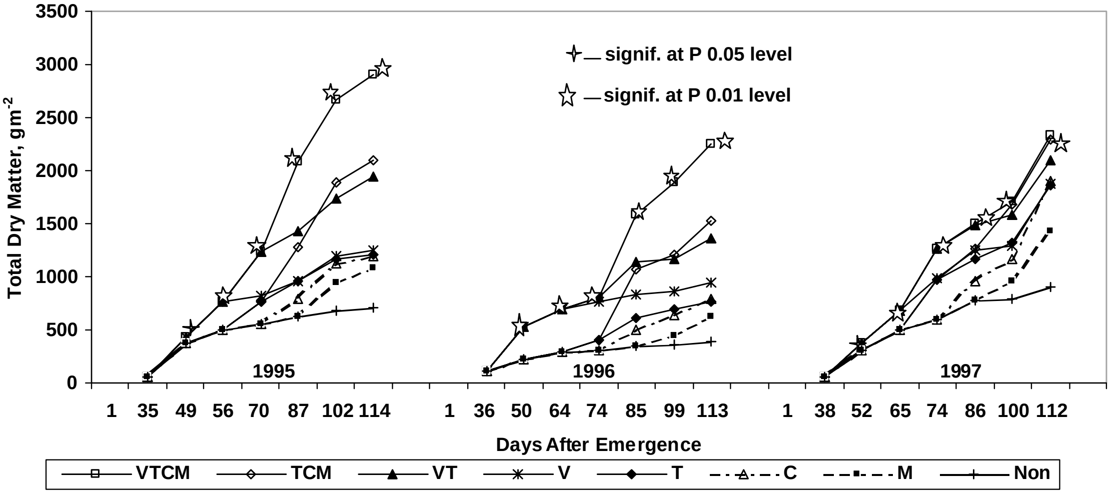

Fig. 4. Total above ground dry matter accumulation under various water stress conditions, (year × treatment interaction for the final values is significant at $P < 0.01$ level).

In case of the treatments that omitted two or three irrigation applications, the effect of water stress was more pronounced. The dry matter weight loss under these treatments varied in the ranges of 57–63, 58–66 and 20–38% for 1995–1997 years, respectively. As could be expected, the most severe effect of water deficits on dry matter loss was observed for the non-irrigated treatment. While dry matter loss under different stress levels of the wet year was determined to be in the ranges of 20–38% (non-irrigation excluded), much higher loss rates varying in the ranges of 58–73%, appeared as a result of the drought experienced in 1996.

Biomass production of 2300–3000 g m^{-2} accumulated under the most favourable moisture condition (VTCM) is consistent with previous reports (Inthapan and Fukai, 1988). Short-term water stress effects at the beginning of intensive vegetative growth stage on dry matter have also been reported by other authors (NeSmith and Ritchie, 1992; Salvador and Pearce, 1995), and could be explained by a decline in plant extension growth, delayed leaf tip emergence and limited leaf size (the photosynthetic factory). Jama and Ottman (1993) have studied the effect of water stress during early growth stages, including anthesis, and found that delay in the first irrigation reduces dry matter accumulation rate at all growth stages up to milk stage. Significant rates of dry weight loss due to short-term water deficit in soil during the following stages, probably appeared as a consequence of reduced leaf area increase and stem internode elongation, delayed ear and ovule development, decreased number of kernels due to poor pollination, as well as reduced starch accumulation in the endosperm.

3.2. The effects of water stress on yield and yield components

3.2.1. Grain yield

Data obtained from the 3-year study showed that grain yield was significantly ($P < 0.01$) affected by soil water deficits (Table 5). On the other hand, yields of specific treatments were closely dependent on precipitation and its distribution during the crop cycle. As is evident, moisture stress in one or in two sensitive (tasselling and/or ear formation) stages resulted in serious grain yield reduction. The yield of any treatment exposed to water stress at one or more growth stage was significantly lower than the fully irrigated (VTCM) control treatment during all experimental years. While the grain yields recorded for the latter exceeded 13.84, 10.38 and 13.10 t ha^{-1}, respectively, for 1995–1997 treatments with water deficit in tasselling (VCM) or ear formation (VTM) or during the both stages (VM), yielded only 9.99, 5.33 and 11.19; 9.70, 7.67 and 10.90; and 4.70, 0.68 and 9.58 t ha^{-1}, respectively. Relatively high yields of 13.24, 9.16 and 11.60; and 10.44, 7.50 and 11.20 t ha^{-1} were observed for treatments with an irrigation omission in vegetative (TCM) and milk stage (VTC), showing the relative tolerance of corn to water shortage in the soil profile during these stages.

Comparison among treatments irrigated only once at a particular growth stage shows the significance of irrigation application during the sensitive flowering stage even more clearly. The highest grain yields 5.91, 0.46 and 10.39; and 7.02, 3.84 and 9.24 t ha^{-1} were recorded for treatments with a single irrigation in tasselling and ear formation stages, respectively.

Table 5
The effect of irrigation treatment on grain yield (kg ha^{-1})

Treatments	Years			Average
	1995	1996	1997	
VTCM	13841 a	10376 a	13095 a	12438
TCM	13239 a	9156 ab	11596 ab	11330
VCM	9986 b	5329 de	11190 ab	8835
VTM	9695 b	7673 bc	10904 ab	9424
VTC	10443 b	7498 c	11198 ab	9713
VT	5783 de	3457 f	9661 b	6300
VC	7246 cd	2707 g	9683 b	6545
VM	4703 ef	679 h	9580 b	4987
TC	10843 b	6577 cd	10257 b	9226
TM	9940 b	7770 bc	11549 ab	9226
CM	8873 bc	4416 ef	11145 ab	8145
V	3608 fg	698 h	7316 cd	3874
T	5902 de	4584 ef	10397 b	6960
C	7020 cd	3835 fg	9239 bc	6698
M	4897 ef	1086 h	9238 bc	5074
Non	2014 g	1105 h	6322 d	3147
x (overall mean)	8002	4809	10148	
Sx	464.84	329.60	528.24	
Sd	657.38	466.13	747.04	
Cv	8.2	9.7	7.4	
Year				**
Year × treatment				**

** Means within columns not followed by the same letter are significantly different at the $P < 0.01$ level by Duncan's multiple range test.

The performance of the irrigation treatments was affected to a large extent by the amount and distribution of seasonal precipitation. Grain yields were significantly reduced by the 1996 drought, with a statistically significance of year × treatment interactions at $P < 0.01$ level. Although drought symptoms were visible and significant in all the plots, the grain yield of the treatments with projected water deficit during one of the sensitive stages (e.g. VCM and VTM) were dramatically decreased in 1996 compared to the previous year. The effect of the drought was much more severe in the treatments with projected water shortage in the soil profile during tasselling and ear formation stages. Some treatments such as VM and V yielded even less than the rain fed treatment. On the contrary, precipitation during the sensitive growth stages of the last experimental year (1997), improved the performance of the treatments that allowed water stress to develop during the tasselling and/or ear formation stages.

Results obtained from the study concerning the effect of timing of water deficit on grain yield are comparable with those published earlier (Doorenbos and Kassam, 1979; Musick and Dusek, 1980). Robins and Domingo (1953) working with maize in pots reported that even 2- or 7-day long water stress in the tasselling stage leads to grain yield reduction up to 22 and 50%, respectively. NeSmith and Ritchie (1992) evaluated short- and long-term responses of corn to a pre-anthesis water deficit and described yield losses of 15–25% as long-term consequences of water stress. Field trials carried out in the Central Anatolian part of Turkey showed that corn is very sensitive to water deficits at tasselling and silking stages and is more tolerant at knee height and milk stages (Ogretir, 1994).

3.2.2. Grain yield per ear and ear number per plant

Similar results of water stress due to omission of irrigation application are recorded in terms of grain yield per year (Table 6). Maximum grain yields per ear during the experimental years, 0.24, 0.18 and 0.20 and 0.24, 0.14 and 0.17 kg per year, were obtained from full irrigated control (VTCM) and the treatment TCM, respectively. Corn grown under conditions of water

Table 6
The effect of water stress on grain yield per ear and ear number per plant

Irrigation treatments	Grain yield (kg per ear)			Average	Ear number per plant			Average
	1995	1996	1997		1995	1996	1997	
VTCM	0.24 a	0.18 a	0.20 a	0.21	1.08 abc	1.00 ab	1.18 a	1.09
TCM	0.24 a	0.14 ab	0.17 abc	0.18	1.04 abc	1.07 ab	1.13 ab	1.08
VCM	0.19 b	0.08 cd	0.19 a	0.15	0.99 bc	1.12 a	1.01 bcdef	1.04
VTM	0.18 bc	0.14 b	0.17 ab	0.16	0.99 bc	0.92 ab	1.02 bcdef	0.98
VTC	0.18 bcd	0.13 b	0.20 a	0.17	1.11 ab	0.98 ab	1.00 bcdef	1.03
VT	0.11 fgh	0.07 de	0.17 abc	0.12	0.95 c	0.85 b	1.03 bcdef	0.94
VC	0.14 cdef	0.05 de	0.18 abc	0.12	0.94 c	0.82 b	0.97 cdef	0.91
VM	0.13 efg	0.07 de	0.19 ab	0.13	0.66 d	0.19 d	0.92 def	0.59
TC	0.18 bcd	0.11 bc	0.15 bcd	0.15	1.15 a	1.00 ab	1.05 abcde	1.07
TM	0.18 bcd	0.14 b	0.18 ab	0.17	1.05 abc	0.96 ab	1.06 abcd	1.02
CM	0.17 bcde	0.07 cde	0.19 a	0.14	0.97 bc	1.00 ab	1.00 bcdef	0.99
V	0.10 gh	0.06 de	0.14 cd	0.10	0.70 d	0.19 d	0.90 ef	0.60
T	0.11 fgh	0.08 cd	0.16 abc	0.12	0.98 bc	0.95 ab	1.09 abc	1.01
C	0.14 def	0.07 de	0.18 abc	0.13	0.94 c	0.90 ab	1.07 abcd	0.97
M	0.13 fg	0.04 e	0.17 abc	0.11	0.71 d	0.51 c	0.98 bcdef	0.73
Non	0.09 h	0.05 de	0.11 d	0.08	0.42 e	0.35 cd	0.89 f	0.55
x (overall mean)	0.157	0.093	0.175		0.92	0.80	1.02	
Sx	0.0093	0.0083	0.0087		0.0326	0.0555	0.0337	
Sd	0.0132	0.0117	0.0124		0.0461	0.0785	0.0477	
Cv	8.4	12.5	7.1		5.0	9.8	4.7	
Year				**				**
Year × treatment				**				**

** Means within columns not followed by the same letter are significantly different at the $P < 0.01$ level by Duncan's multiple range test.

deficit in both sensitive stages (V, M and VM) gave the least grain weight per year.

These results support the view that water stress at different growth stages affect grain weight per ear to a greater or less degree depending on stage (Bajwa et al., 1987; Roy and Tripathi, 1987). Kanber et al. (1990) reported that grain yield per ear changes with the application stage and irrigation water amount, and noted that a close relationship exists between irrigation water amount and ear size.

The number of ears per plant was also significantly affected by water stress during any growth stage (Table 6). The highest ear number was determined for VTCM, TCM, VTC and TC treatment, all included water application during the both sensitive stages. Ears per plant varied in the ranges of 1.0–1.18, 1.04–1.13, 0.98–1.11 and 1.00–1.15 for these treatments respectively. Variation was larger in range (0.35–0.88, 0.19–0.90, 0.51–0.98 and 0.19–0.92) under rain fed conditions and in the irrigation programs (V, M and VM) that allowed water deficit during the sensitive stages.

Ear number per plant for the treatments most favourable for soil moisture appeared to be in the ranges of 5.92–6.22 m^{-2}, close enough to values of 5.2–6.4 m^{-2} obtained by Jama and Ottman (1993). Roy and Tripathi (1987) have also shown the positive effect of shorter irrigation intervals on ear number per plant and grain yield per ear, under growing conditions of West Bengal.

3.2.3. Kernel weight and kernel number per ear for plants with ears

Observations of kernel weight and kernel number per ear for plants that have ears are summarised in Table 7. Data in the table show that both yield parameters are significantly ($P < 0.01$) affected by water deficits in the soil profile. The highest average weight of 1000 kernels, in the ranges of 257–283 g, was recorded for the treatments including irrigation application at the milk stage. The fact that 1000 kernel weights of the M and VM treatments, irrigated only once or twice during the entire growing season, were

Table 7
The effect of water stress on kernel weight and kernels per ear for the plants with ears

Irrigation treatment	Kernel weight (g/1000)			Average	Kernels number per ear for plants with ears			Average
	1995	1996	1997		1995	1996	1997	
VTCM	288.9 a	285.6 ab	274.3 a	282.9	778 ab	636 a	708 ab	707
TCM	277.5 ab	237.1 cde	269.7 abcd	261.4	807 ab	635 a	667 ab	703
VCM	256.7 bcd	309.9 a	281.3 a	282.6	690 abcd	269 de	688 ab	549
VTM	240.1 def	257.7 bc	278.0 a	258.6	713 abc	569 ab	676 ab	653
VTC	218.8 efg	211.1 defg	265.0 abcd	231.6	801 ab	637 a	738 a	725
VT	176.2 i	172.8 hi	248.3 bcde	199.1	608 bcde	411 bcd	658 ab	559
VC	209.9 ge	285.9 ab	256.0 abcde	250.6	645 bcd	203 e	680 ab	509
VM	246.3 cde	279.7 ab	280.7 a	268.9	509 de	273 de	651 ab	478
TC	191.2 hi	190.2 fghi	277.0 a	219.5	865 a	603 a	623 abc	697
TM	237.1 defg	231.3 cde	275.3 ab	247.9	715 abc	613 a	696 ab	675
CM	256.7 ab	285.7 ab	280.7 a	274.4	571 cde	271 de	695 ab	442
V	165.2 i	181.9 ghi	229.7 e	192.3	547 cde	382 cd	620 abc	516
T	174.3 i	156.8 I	242.3 de	190.8	608 bcde	517 abc	691 ab	605
C	215.5 fgh	204.3 efgh	242.3 de	220.7	609 bcde	445 bc	628 abc	560
M	273.0 abc	249.8 bcd	281.7 a	268.2	442 e	172 e	588 bc	394
Non	170.7 i	223.9 cdef	247.0 cde	213.9	509 de	250 de	500 c	419
x (overall mean)	226.6	235.2	264.3		651	430	656	
Sx	6.24	8.73	6.20		44.08	37.91	32.20	
Sd	8.82	12.34	8.77		62.33	53.61	45.53	
Cv	3.6	5.2	3.3		6.9	12.4	9.6	
Year				**				**
Year × treatment				**				**

** Means within columns not followed by the same letter are significantly different at the $P < 0.01$ level by Duncan's multiple range test.

higher even than the high yielding VTC and TC treatments showed the determinative effect of moisture availability in the soil profile during the period forthcoming grain filling. Greater kernel weight of M and VM treatments could be explained with fewer kernels set due to water stress at flowering and better grain feeling in the presence of fewer kernels per an ear. Lower values obtained for the treatments providing relatively favourable moisture conditions (VTC and TC) for the major part of the growing season, could be due partly to the strong competition for water and assimilates during the process of grain filling. Moreover, NeSmith and Ritchie (1992) reported varying responses in grain weight due to water deficits at pre-anthesis, and considered these a consequence of the procedure that includes weighing of a large sample of seed, and then dividing by seed number, which assumes an equal distribution of seed size among treatments.

A statistically significant ($P < 0.01$) effect of moisture deficits allowed at different growth stages has been observed on kernels number per ear for plants that have ears (Table 7). The lack of water in the soil profile at critical tasselling and ear formation stages dramatically decreased the kernel set on the ear. As is evident from data in the table, the kernels number of any treatment exposed to water stress at one or both the critical stages was much lower than that of the fully irrigated control, TCM, VTC and TC treatments, all receiving irrigation water at both tasselling and ear formation. Only one irrigation omitted at tasselling (VCM) lead to a 20% decrease in kernel number on average. Much higher kernel reductions (32–35%) were found for the case when plants were exposed to water stress at both these stages (VM). The effect of water availability or deficiency in the soil root zone on kernel number during the processes of pollination and kernel set is much better illustrated by kernel number estimated for treatments irrigated only once at tasselling and ear formation, and exposed to water deficits during the remainder part of the growing season. Nevertheless, they were exposed to moisture stress during the major part of the season, but resulted in an average kernel number per ear of 605 and 630, respectively. Severe drought condition experienced during 1996 enhanced the effect of water deficits on kernel number (Table 7) in almost all treatments.

Results presented here agree with the work of others who have exposed corn plants to single soil moisture stress periods during different stages of plant development and clearly indicate that moisture stress at flowering has a strong effect on kernel number per year and per plant. Yazar et al. (1999) reported that kernel number per plant is moisture stress-dependent and concluded that kernel number decrease is the primary effect of water deficit on corn grain yield. Zinselmeier et al. (1999) reported that plants exposed to low water potential (Ψ_w) 5 days around pollination allowed embryos to form, but ovary starch was depleted and abortion occurred. Moreover, according to Westgate and Boyer (1986) stress shortly after pollination reduces the number of pollinated kernels as a result of kernel abortion prior to onset of the storage phase. Setter et al. (2001) evaluated the processes of kernel setting under a 5 days water stress and shading at the pre-pollination and early post-pollination stages, and determined that water deficit substantially increased ABA concentrations in all reproductive tissues of corn. They suggested that ABA may play a role in the loss of kernel set within apical regions of an ear in response to water deficit.

3.3. Seasonal irrigation water requirements and evapotranspiration

Irrigation water amounts applied to the experimental treatments and seasonal water consumption values for the experimental years are presented in Table 8.

Total irrigation water applied to irrigation treatments was strongly affected by the amount and distribution of precipitation during the trial years. Due to the relatively high rate and favourable distribution of the precipitation during the last year, irrigation water amounts applied at ear formation and milk stages were less than in 1995 and 1996. Seasonal water amounts of 525 and 574 mm applied to the adequate irrigated treatment in 1995 and 1996 are in agreement with those of 568 and 505 mm reported by Cavero et al. (2000) for the semiarid region of Spain. Yazar et al. (2002) applied a total of 581 mm irrigation water amount to drip irrigated corn in southeast Turkey. Much lower seasonal irrigation water amounts and seasonal ET values have been reported for the coastal part of Thrace (Istanbulluoglu et al., 2002) and Black Sea region of the country

Table 8
Seasonal irrigation water quantities and water consumption of corn (mm) affected by year and treatment

Experimental treatment	Experimental years						Average		Irrigation number
	1995		1996		1997		I	ET	
	I	ET	I	ET	I	ET			
VTCM	524.8	794.8	574.3	782.0	386.9	710.1	495.3	762.3	4
TCM	434.0	691.0	466.9	643.3	329.9	650.8	410.3	661.7	3
VCM	372.6	622.0	392.5	600.5	235.8	560.7	333.6	594.4	3
VTM	368.0	643.6	427.2	616.8	294.4	630.6	363.2	630.3	3
VTC	399.8	631.1	436.1	637.0	300.6	628.1	378.8	632.1	3
VT	243.0	478.2	289.2	507.8	208.1	543.1	246.8	509.7	2
VC	247.6	481.4	254.5	471.3	149.5	499.3	217.2	484.0	2
VM	215.8	460.4	245.4	446.1	143.3	470.2	201.5	458.9	2
TC	309.0	553.1	328.9	520.9	243.6	570.8	293.8	548.3	2
TM	277.2	515.7	319.8	539.0	237.4	566.6	278.1	540.4	2
CM	281.8	528.1	285.1	497.8	178.8	562.3	248.6	529.4	2
V	90.8	322.9	107.4	313.2	57.0	409.3	85.1	348.5	1
T	152.2	374.3	181.8	371.8	151.1	478.8	161.7	408.3	1
C	156.8	338.0	147.1	342.0	92.5	409.2	132.1	363.1	1
M	125.0	360.0	138.0	339.5	86.3	475.2	116.4	391.6	1
Non	0	230.1	0	214.1	0	349.6	0	264.6	0

(Bayrak, 1979), probably because of higher atmospheric relative humidity.

3.4. Crop–water relationships and yield response factor (k_y) for corn

The relationships between seasonal evapotranpiration and grain yield have been evaluated for each experimental year (Fig. 5 and Table 9). Results of the regression statistical analysis showed that close relationship exists between the total seasonal evapotranspiration and grain yield for each experimental year. The response of yield to water supply can be quantified through the yield response factor (k_y) which relates relative yield decrease to relative evapotranspiration deficit. Evapotranspiration and yield data obtained from the experiment were evaluated using the model (Eq. (1)) described by Stewart et al. (1977).

The slope of the fitted regressions (Fig. 6) represents the yield response factor (k_y). Values of k_y for a given crop and locality varied from year to year even at the same location. As it is evident from the slope of the

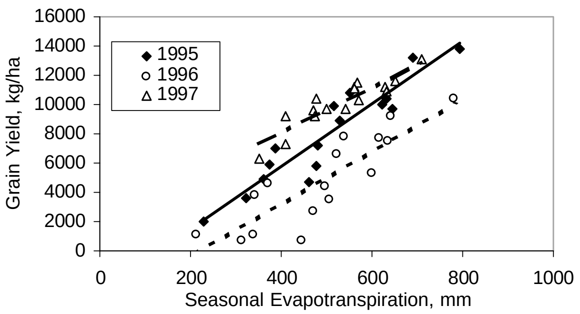

Fig. 5. Relationship between seasonal evapotranspiration and grain yield. $^{**}P < 0.01$ level.

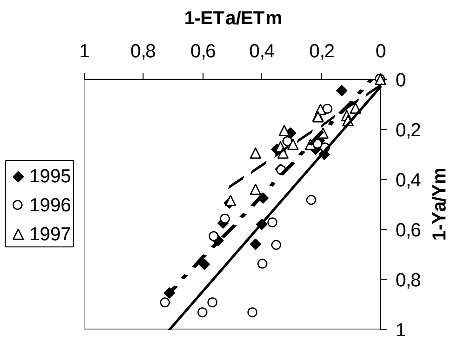

Fig. 6. Relationship between relative evapotranspiration deficit ($1-ET_a/ET_m$) and relative yield decrease ($1-Y_a/Y_m$). $^{**}P < 0.01$, k_y slope.

Table 9
Crop–water relationships and the yield response factor (k_y) of corn

Experimental year	Crop–water relationships (regression equation)	Yield response factor (k_y) (regression equation)	R^2
1995	$Y^a = 21.327ET - 2759.9$	$1-(Y_a/Y_m) = 122^b\,[1-(ET_a/ET_m)]-0.03$	0.88^{**}
1996	$Y = 18.09ET - 4059.7$	$1-(Y_a/Y_m) = 1.36[1-(ET_a/ET_m)]-0.03$	0.74^{**}
1997	$Y = 14.479ET + 1910.3$	$1-(Y_a/Y_m) = 0.81[1-(ET_a/ET_m)]-0.02$	0.83^{**}

[a] Grain yield.
[b] k_y value.
** $P < 0.01$.

curves plotted on the figure, the highest yield reduction due to water stress, i.e. the highest value of k_y (1.36), occurred during the season which experienced severe drought (1996), when the total seasonal precipitation was only 49 mm. On the other hand, the value of k_y was much lower (0.81) for the rainy 1997 when the total seasonal precipitation rate exceeded 200 mm. Values of yield response factor (k_y) obtained from the study are consistent with those of 1.12–1.39 determined by Retta and Hanks (1980) and 1.25 reported by Doorenbos and Kassam (1979), but lower than the 1.47 reported by Howell et al. (1997) for Bushland, TX. The average k_y value of 1.29 determined from our study is higher than that of 0.93 pointed out by Kanber et al. (1990) for the coastal part of Cukurova and that of 0.76 estimated for the coastal part of Thrace by Istanbulluoglu et al. (2002). This disagreement could be explained by the high relative humidity and different precipitation characteristics of the coastal areas. Moreover the value reported by Kanber et al. (1990) was obtained from an experiment with corn grown as a second crop after wheat.

4. Conclusions

As a result of 3-year study it was concluded that vegetative growth is strongly affected by water stress at different growth stages. A water deficit during the rapid vegetative growth stage decreased plant height. Irrigation applied just at the beginning of tasselling dramatically accelerated plant growth and the effect was obvious as early as several days after water application. As a general rule, leaf area index increased under favourable soil moisture conditions (VTCM) until 70–80 days after emergence, and then decreased as the older leaves died. Water stress during vegetative growth and tasselling stages, reduced LAI values due to a reduced size of the leaves. Moisture stress during the ear formation and milk stages, causes early loss of lower leaves and decreases dry matter weight and grain yield as a result of reduced intercepted radiation.

Results of the study also show, that all the yield parameters discussed in this paper are significantly affected by irrigation application or water shortage in the soil profile during the sensitive tasselling and ear formation stages.

High grain yields (9–13 t ha^{-1}) are obtainable by application of 400–450 mm irrigation water amount (TCM). However, even a single irrigation omission during one of the sensitive growth stages, may cause a 30 and 40% grain yield loss during dry years as 1996. Much higher grain yield losses of 66–93% should be expected as a result of prolonged water stress, due to irrigation omission during both the tasselling and ear formation stages.

A close linear relationships between seasonal evapotranspiration rate and yield exists during dry, rainy and years of normal precipitation amount and distribution. Results obtained from treatments with less irrigation number could be used as a good basis for reduced irrigation strategy development in regions with a serious water scarcity problem. When water available is sufficient only for one or two irrigation applications, the most beneficial water use can be achieved by irrigations applied at tasselling and/or cob formation stages. The yield response factor (k_y) obtained for years of different precipitation characteristics could be used for the purposes of irrigation management and water allocation scheduling over irrigation schemes with uncontrolled and limited irrigation water supply.

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