Pak. J. Agri. Sci., Vol. 54(1), 209-216; 2017
ISSN (Print) 0552-9034, ISSN (Online) 2076-0906
DOI: 10.21162/PAKJAS/17.3938
http://www.pakjas.com.pk

RESPONSE OF MAIZE TO PARTIAL-ROOT-DRYING IRRIGATION

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In this study, the yield response of maize species was investigated under different irrigation levels and techniques. Three irrigation treatments compared were T_1) Control in which the needs of the plants for water were fully met; T_2) Partial-root-drying (PRD) treatment where the same amount of water that was applied under the DI (i.e., 65% of that applied under control treatment) was applied to wet alternately only one halve of the plant roots leaving the other half dry in each irrigation; T_3) Deficit Irrigation (DI) which received 65% of total water needed by the control. However; both halves of the plant roots were equally wetted under the deficit irrigation treatment, T_3. Therefore, the wetted side changed in every irrigation under the PRD treatment. The data obtained in PRD and DI plots were compared to those in control treatment. The maize crop yields followed the rank $T_1>T_2>T_3$. The water-use efficiency (WUE) was the highest under the PRD treatment. Crop response factors (Ky) changed within the range from 0.75 to 1.37 under the PRD treatment, from 1.13 to 1.78 under the DI treatment. The Ky data therefore suggested that deficit irrigation under the PRD technique caused proportionally less crop yield decrease as compared to the DI technique. The mid-day leave water potential (LWP) data was influenced essentially by the practices not with the crop species. The predawn LWP values increased as the soil water content increased with the irrigation. Under the DI treatment, water stress was more evident compared to the other treatments. It was noted that plants showed better capability for surviving water stress if irrigated with the PRD practice. The maize, to this effect, showed specie-dependence. The species Tector and Tietar were selected as the best species, showing no significant yield decrease under the deficit irrigation if irrigated with the PRD.
Keywords: Deficit irrigation, crop yield response, midday LWP, predawn LWP, maize species, stored water.

INTRODUCTION

The new irrigation techniques with higher water application efficiency should replace the commonly used traditional methods of irrigation in order to increase agricultural production for compensating the decrease of land and water resources, largely allocated to municipal and industrial usage. To this effect, a new innovation for deficit irrigation, called "partial root-drying" (PRD) practice, is promoted in recent years. In PRD technique, irrigation water quantity applied normally under the traditional irrigation practices is reduced in a certain portion, wetting only halves of plant roots and leaving other halves dry. In the following irrigation, the other halves get wet. In this way, the aim is to use limited water resources more efficiently; similar to what is achieved with the traditional deficit irrigation practices (Kang *et al.*, 1998). In the PRD technique, while halves of the plant roots were wetted, the other halves were relatively left dry.
According to PRD practices, plant roots were divided into two parts and each was grown in separate pots. Plants could keep growing while watering only one of the pots, and leaving the other dry. Under such cases, stomas are relatively closed and thus evapotranspiration reduces (Zhang *et al.*, 1987; Davies and Zhang, 1991). It was suggested that the closure of stomas when halves of the roots were exposed to drought is controlled via chemical signals transferred from roots to the leaves (Davies and Zhang, 1991; Tardieu and Davies, 1992). While these signals reduce vegetative growth of the plant, they stimulate generative growth. In the case of wetting only halves of the roots and leaving the other halves dry, the abscisic acid concentration in xylem elements increases and causes stomatal closure (Stoll *et al.*, 2000). The change in root water potential and rise of pH in xylem were other signals shown to be effective in controlling stomatal closure in leaves (Wilkinson and Davies, 1997).
In numerous studies reported on the field-PRD-irrigation technique, only one species of plant was used. Different responses of plant species to different deficit irrigation practices were not focused on. Although Kang *et al.* (2000) and Kirda *et al.* (2005) used the same plant species in their work, their reported maize-crop-yield results obtained using PRD irrigation were different possibly due to the different climatic and soil characteristics. In this study, the response of five different maize species were studied under the traditional deficit and PRD irrigation technique, to investigate the hypothesis that maize crop yield response to different modes of deficit irrigation (i.e., DI or PRD) may genetically be controlled. Partial results such as yield, irrigation water-use

Table 1. Some physico chemical properties of the experimental soil.

Depth (cm)	FC	PWP	BD	pH	EC	OM	TN	Texture
0–30	0.40	0.26	1.19	7.8	0.25	0.80	0.075	C
30–60	0.40	0.26	1.19	7.7	0.18	0.55	0.045	C
60–90	0.41	0.28	1.16	7.7	0.19	0.30	0.025	C
90–120	0.41	0.28	1.25	8.0	0.16	0.06	0.004	C

FC, field capacity (cm^3 cm^{-3}); PWP, permanent wilting point (cm^3 cm^{-3}); BD, bulk density (g cm^{-3}); pH, pH in water; EC, electrical conductivity (dS m^{-1}); OM, organic matter (%); TN, total nitrogen (%).

efficiency, mid-day leaf water potential, root-density distribution and so on were earlier published by Kaman *et al.* (2011). However, further data on irrigation water requirement, soil water content, and crop yield response factors (ky) and predawn leaf water potential will be presented and discussed in this study.

MATERIALS AND METHODS

The study was conducted at Çukurova University, in the research station of Faculty of Agriculture (36°59´N, 35°18´E). The research area was in the Mediterranean climate zone where the summers are hot and dry, and the winters are warm and wet. The area receives almost all of its precipitation during the winter months. The average annual precipitation is about 650 mm, occurring throughout the year with non-homogenous distribution pattern. However, there was essentially no influence of rainfall on the experimental treatments because the research work was carried out in summer months when there was no rainfall. The soils of the research area belong to Mutlu series. The topography of the research area is plain or almost plain, with the altitude of 20 meters above the sea level. Soil profile mostly consists of clay which has swelling characteristics. As shown in Table 1; the test soil has pH 7.7–8.0; electrical conductivity (ECe) 0.16–0.25 dS m^{-1}, bulk density (ρ) 1.16–1.25 g cm^{-3}, water content of at field capacity (FC) 0.40–0.41 cm^3 cm^{-3} and soil permanent wilting point (PW) 0.26–0.28 cm^3 cm^{-3}. The area had no soil salinity problems.

The irrigation water used in the study was diverted from the YS1 main irrigation canal of the North Yuregir Irrigation Union and conveyed through Cukurova University Agricultural Research Fields. Irrigation water samples taken from the irrigation canal were analyzed following the methods discussed in USSL (1954). Irrigation water salinity analysis showed that the water was of good quality. The irrigation method used was the drip irrigation technique with the drip laterals located centrally between the plant rows. The distance between the drippers was 33-cm with the dripper flow rate of 4 L h^{-1}. The study included three irrigation treatments, T_1, T_2 and T_3 (Table 2).

Table 2. Irrigation treatments.

Treatments	Description
T_1 (Control)	The control treatment where plant water requirement, 100% Class-A pan evaporation, was fully met and the furrows on both sides of the plant rows were irrigated.
T_2	35% deficit irrigation, compared to T_1 control treatment, was applied in every other furrow thus irrigating only one side of the plant rows. The furrows irrigated were alternated every irrigation.
T_3	The same amount of water as T_2 was applied in furrows on both sides of the plant rows, in similar way to T_1 control treatment.

As the five species of maize P.31.G.98, P.3394, Rx:9292, Tector and Tietar were used as the second crop, following the wheat harvest. The maize crop was planted in the distance of 70-cm between the rows and P × P distance 18-cm. The first year planting was done on July 24, 2004, and the next was on July 22, 2005. The first year harvest was done on November 1, 2004, and the second year harvest was on November 10, 2005. In the study, split-plot experimental design was used with the irrigation treatments being the main treatments and maize species being the sub-treatments. Four replicates were used. Each plot was 8 m long, 4.9 m wide and had 7 rows of plants.

As fertilizer, 30 kg da^{-1} nitrogen (N), 13 kg da^{-1} phosphor (P), 11 kg da^{-1} potassium (K) were applied through using fertilizer sources, urea, triple super phosphate (P_2O_5) and potassium sulfate (K_2O), respectively. All the phosphorous and potassium fertilizers and 1/3 of nitrogen fertilizer were applied as the base-fertilizer before planting. The remaining nitrogen was applied in two split dose before the first and the second irrigation.

Experimental data on soil water content, leaf water potential (LWP), irrigation water requirement, evapotranspiration (ET), crop yield response factor (Ky) were measured and recorded in the study. The soil water content was routinely measured using neutron meter technique. For LWP measurements, Scholander cup (PMS, Corvallis, USA) was used.

The irrigation water requirement [(I, (L)] for the T_1 control treatment was calculated using the Class-A pan evaporation data ($I = K \times Ep \times A$).

In the equation, K represents evaporation pan to plant ratio (K=1); Ep represents total evaporation from the Class-A pan during the irrigation period (mm); A represents the area to be irrigated (m^2). The first irrigation was initiated as the total available soil water content was depleted to 50%. The subsequent irrigations were planned once a week. In this way, the total of 9 irrigations was used in the research years.

In addition to irrigation water records, rainfall data was also recorded. Using the mentioned data, the crop water consumption ET was calculated using the water budget equation:

$$ET = I + P - D - R \pm \Delta S$$

In this equation, ET represents water consumption of plants (mm); I represent irrigation water (mm); P represents precipitation (mm); D represents drainage (mm); R represents run-off (mm); ΔS represents the changes of soil water storage difference between the beginning of the season and the harvest (mm). Because the irrigation method used in the study was the drip system, we could safely assume that drainage water was essentially zero (i.e., D=0). Similarly, the run-off was also zero (R=0).

In the planning irrigation practices, the crop yield response factor (Ky) is an important parameter. The Ky showing the crop response to the deficit irrigation was calculated with the following equation developed by Stewart *et al.* (1977).

$$1 - Y \times Y_m^{-1} = Ky\left(1 - ET \times ET_m^{-1}\right)$$

In this equation, Y represents the actual crop yield (t ha^{-1}) obtained under the existing watering conditions, as practiced in each irrigation treatment, Ym represents likely the maximum crop yields (t ha^{-1}) if no water deficit occurs, Ky is the crop yield response factor which represents the yield reduction due to the deficit evapotranspiration, ET represents the actual water consumption (mm) in the conditions where plants were grown, ETm represents the maximum water consumption throughout the growing season when there is no water deficit (mm).

Ky values will show the probable effects of the deficit irrigation practices on the crop yield change depending on the irrigation technique. Statistical analysis of the research data was done using the program Statistix® for Windows (1996) (Analytical Software, Tallahasse, FL, USA). The difference between the treatment means was compared using the LSD values (P=0.05).

RESULTS

***Soil water content*:** The highest water content in the plant roots of the maize species within the 90 cm soil depth was recorded under the T_1 treatment in 2004 (Fig. 1). Data from in 2005, not reported here, showed a similar trend. Although the same amount of irrigation water was applied to the T_2 and T_3 treatments, the root-zone soil water content was higher in the wet parts of the T_2 treatment. The soil water content in the plant-root zone changed depending on both the plant species and the irrigation treatments.

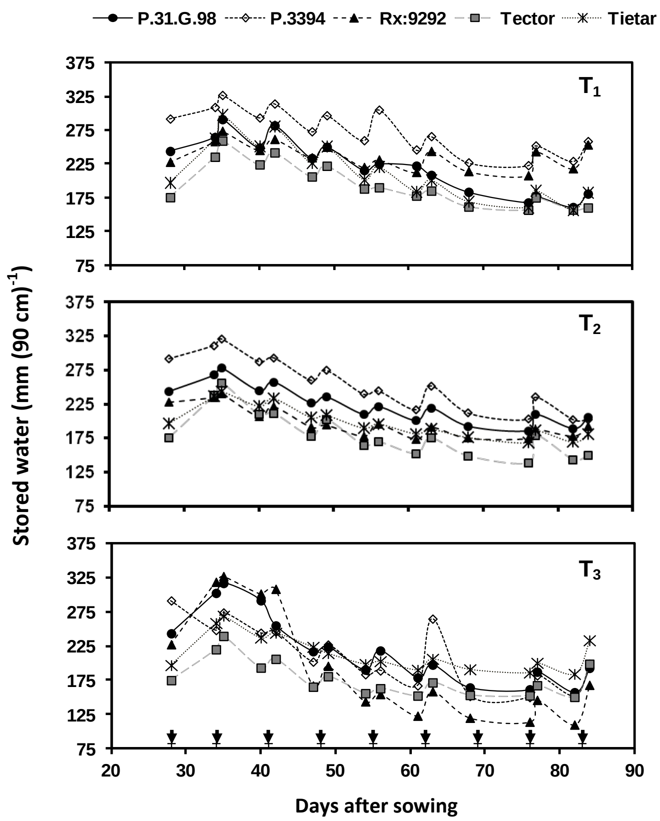

Figure 1. Seasonal change of plant root zone soil-water storage in 2004. Arrows, pointing downward, above the lower x-axis show irrigation time.

The soil water content for the P.3394 was the highest under the T_1 and T_2 treatments (Fig. 1). Similarly, the crop yields for P.3394 were higher under the T_1 and T_2 treatments than those obtained under the T_3 treatment (Kaman *et al.,* 2011). The irrigation water-use efficiency (IWUE) value was the highest under the T_2 treatment (Kaman *et al.,* 2011). In other words, the findings imply that P.3394 maize species used water at highest efficiency. Under the T_1 and T_2 treatments, the species Tector had the lowest root-zone soil water content in the first year. In the second year, the trend had changed somewhat and the species P.31.G.98 under the T_1 treatment and P.31.G.98 and Tector under the T_2 treatment had the lowest soil water content. Under the T_3 treatment however, the species Tector had the lowest soil water content until the mid-season in the first year. From the mid-season until the end, the lowest soil water content was noted with Rx: 9292 maize species. The water consumption of maize species Tector, having proportionally low root-zone soil water content, was higher compared to the other species (P.3394). Under the $-T_3$ treatment in the second year, the species P.3394 had more root-zone soil water content compared to the other species after mid-season. The root-zone soil water content for the species Tietar did not show a consistent trend.

***Crop yield response factor (Ky)*:** The variance analysis showed that the difference between irrigation and maize species was significant. The crop yields obtained under the irrigation treatments showed wide range of variability (1.78 t ha^{-1} and 11.39 t ha^{-1}) with the crop species in both research years. The highest crop yield was noted under the T_1 irrigation treatment (6.97 t ha^{-1} in 2004, 10.39 t ha^{-1} in 2005). The treatment differences for the crop yields followed the rank $T_1>T_2>T_3$, essentially depending on the amount of irrigation water applied (Kaman *et al.,* 2011).

In the second research year, the water-yield relations were used to calculate the crop yield response factor (Ky) shown in Fig. 2. Under the T_3 and T_2 treatments, P.3394 which had the highest crop yield in both years, had the same Ky values (Fig. 2). In other words, the decrease in crop yield due to the water deficit did not depend on the technique. However, for the other four-maize species (P.31.G.98, Rx:9292, Tector and Tietar), the Ky values of the T_2 treatment were lower than those of the Ky values under the T_3 treatment. This implies that the water deficit under the T_2 treatment causes proportionally less crop yield decrease compared to the T_3 treatment (Fig. 2). In particular, the Ky values under the T_2 and T_3 treatments were significantly different for the maize species Rx: 9292 (226%) (P<0.05). In other words, if water deficit is unavoidable, the decreases in crop yield for Rx: 9292 maize species under the T_2 treatment can be insignificant compared to the T_1 treatment. However, it was noted that the maize species, Rx: 9292 had the lowest crop yield compared to the other species (Kaman *et al.,* 2011).

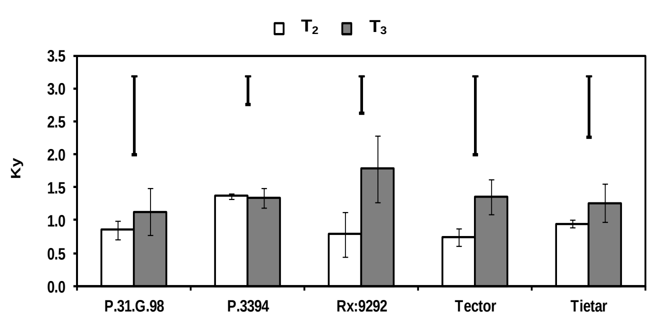

Figure 2. Crop yield response factor (Ky) in 2005. The data points represent means ±S.E. (n=4) and the vertical lines show LSDs at P=0.05.

***Leaf water potential (LWP)*:** Mid-day LWP measurements of the studied maize species were different and showed strong dependence on the irrigation practice used (Kaman *et al.,* 2011; Fig. 3). Under the T_1 treatment, while P.3394 maize species had the highest mid-day LWP values, from mid-season till the end, Tector and Rx: 9292 showed the lowest values. The highest mid-day LWP under the T_2 treatment was observed for P.31.G.98 and P.3394 maize species. The lowest mid-day LWP was recorded for Rx: 9292 in the first and for Tector in the second year. Under the T_3 treatment, Rx: 9292 had the highest mid-day LWP values in the first year. However, in the second year, it was P.3394 having the highest mid-day LWP values. The lowest LWP values were observed with Tector and Tietar in the first and with Rx: 9292 in the second year. It was noted that the decrease of root-zone soil water content for a given maize species followed a decline in mid-day LWP values (Fig.1). Low mid-day LWP values imply that the root-zone soil water content is also decreasing, and thus plants get stressed for water.

For the maize species P.31.G.98 and Tector, the change of mid-day LWP values with the root-zone soil water content was shown in Fig.4. The decrease of root-zone soil water content in the plant roots triggered the decrease. In the cases where soil water content is 250 mm for P.31.G.98, 270 mm and above for Tector, the mid-day LWP values were higher under the T_2 treatment compared to the other treatments (Fig.4).

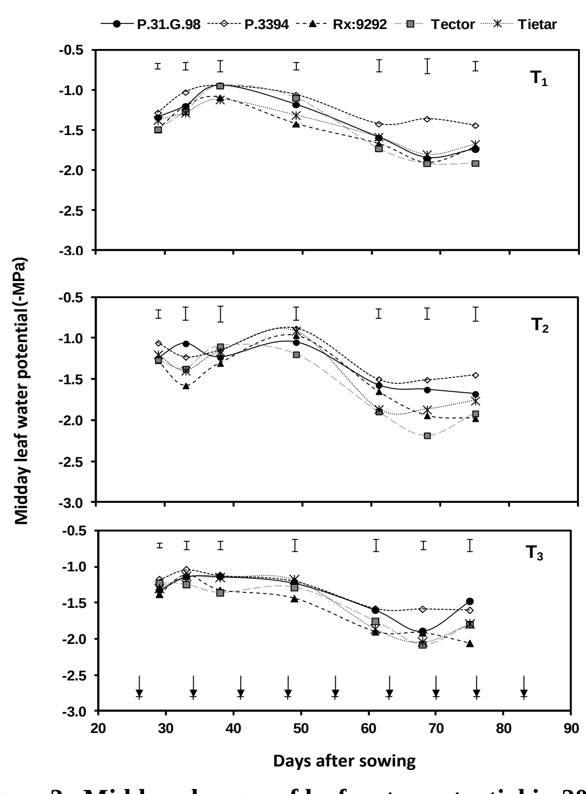

Figure 3. Midday changes of leaf water potential in 2005. Data points are means (n=4) and the vertical lines show LSDs at P=0.05. Arrows, pointing downward, above the lower x-axis show irrigation time.

The root-zone soil water status before sunrise towards morning and in predawn is an important indicator of the effect of water stress. This could be identified through the predawn LWP measurements. During the first year of the study, the predawn LWP measurements (Fig. 5) were made during just before the irrigation and following the irrigation (6^{th} pre-irrigation and post-irrigation). During the second year, similarly the predawn LWP measurements were done (on 4^{th} post-irrigation and 5^{th} pre-irrigation) and the results are shown in Figure 6.

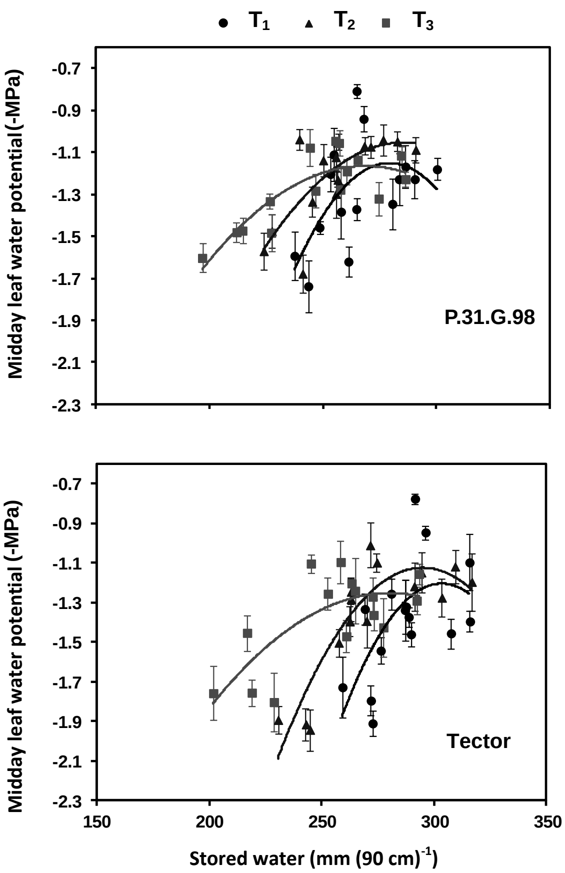

Figure 4. The relationship between midday leaf water potential and soil water content in the genotypes P.31.G.98 and Tector in 2005.

The predawn LWP values before the irrigation were low in both years, and they increased with the increase of root-zone soil water following the irrigation (Fig. 1). Although the same amount of irrigation water was applied to the T_2 and T_3 treatments, the predawn LWP values before the irrigation for P.31.G.98, P.3394 and Tector maize species under the T_3 treatment were lower compared the T_2 treatment (Fig. 5). Thus it can be concluded that water stress under the T_3 treatment strongly manifested itself.

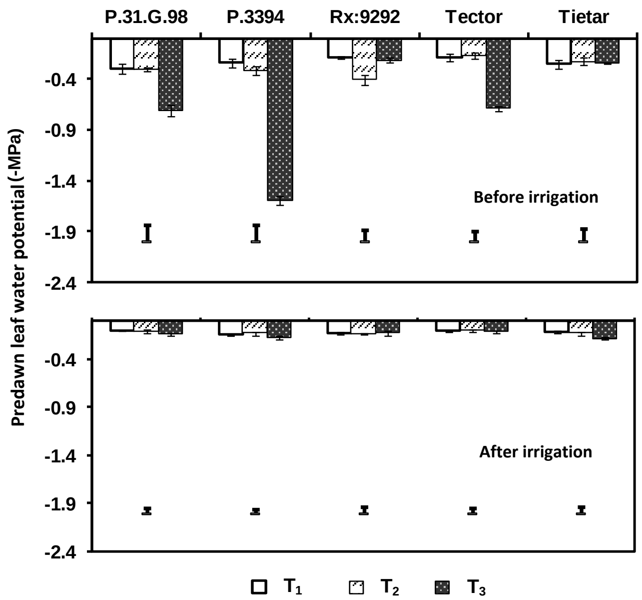

Figure 5. Predawn changes of leaf water potential, before irrigation on 62 days after transplanting and after irrigation on 63 days after transplanting in 2004. LSDs (P=0.05) are presented as vertical line-bars.

DISCUSSION

The root-zone soil water content was lower under the T_2 and T_3 treatments compared to the T_1, full irrigated treatment (Fig. 1). Similar results were reported earlier for different crop species (e.g., Zegbe-Dominguez *et al.,* 2003; Kirda *et al.,* 2004; Kirda *et al.,* 2005; Dorji *et al.,* 2005). It was further shown that the T_2 technique had somewhat higher soil water content compared to that under the traditional deficit irrigation. In other words, the root-zone soil water content was closer to the T_1 treatment under the T_2 practice when compared to the deficit irrigation. The crop yields under the irrigation treatments, depending on the maize species, were different at 5% significance level. The maize crop yields differed greatly depending on the amount of the irrigation water applied under various climatic conditions (Dagdelen *et al.,* 2006). Similarly, in a study carried out in England, the maize crop yield changed from 3.70 t ha^{-1} to 6.70 t ha^{-1} (Ogola *et al.,* 2002), depending on the irrigation water quantity applied. In another study, the maize crop yield changed from 1.58 t ha^{-1} to 3.78 t ha^{-1} (Igbadun *et al.,* 2006).

The crop response factor Ky showing the effect of water deficit on crop yield during the growth season, would vary for different plants (FAO, 1986). The Ky values, commonly used in the studies where the maize water-use efficiency was examined, varied depending on the irrigation technique. In some studies where furrow irrigation practices were used, the Ky value was 0.76 (İstanbulluoglu *et al.,* 2002), changed from

0.81 to 1.36 (Çakır, 2004), and from 1.04 to 1.03 (Dağdelen *et al.,* 2006). In our study, the Ky values changed from 0.75 to 1.37 under the T_2, and from 1.13 to 1.78 under the T_3 treatments. The wide range of variability noted with the Ky values can be attributed to the different crop species and oil characteristics, and of course to the irrigation treatments.

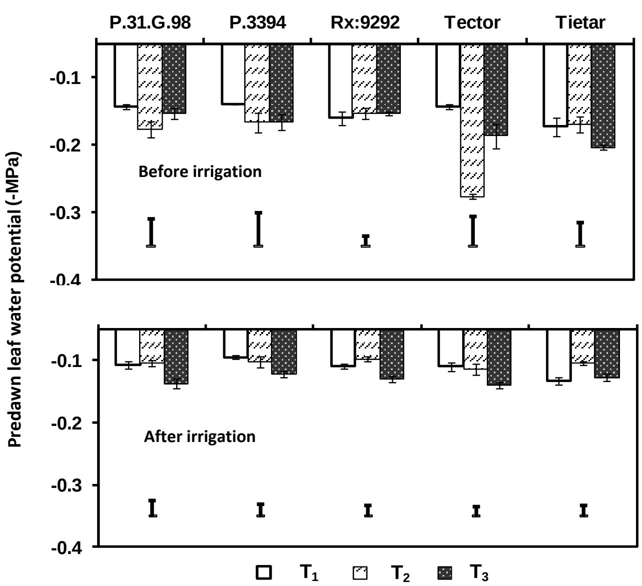

Figure 6. Predawn changes of leaf water potential, after irrigation on 49 days after transplanting and before irrigation on 55 days after transplanting in 2005. LSDs (P=0.05) are presented as vertical line-bars.

In the study, seasonal average mid-day LWP values under the T_1 and T_2 treatments were the highest for the species P.3394 (1st year; between -1.30 MPa and -1.38 MPa, 2nd year; between -1.22 MPa and -1.25 MPa). Thus the data showed that the species in question were not under any water stress. Therefore, the species P.3394 gave the highest yield (Kaman *et al.,* 2011). The high LWP value of P.3394 maize species under the T_2 treatment also explains why WUE value was proportionally higher with these species compared to the other species tested (Kaman *et al.,* 2011). Under the T_1 treatment, Rx: 9292 had the lowest LWP value. Under the T_2 treatment, the species Rx: 9292 in first year, the species Tector in the second year, had the lowest LWP values. Owing to the proportionally low LWP values in Rx: 9292 and Tector maize species, the crop yield and WUE were the lowest under the T_2 treatment compared to the T_1 treatment, confirming the earlier findings by Kaman *et al.* (2011).

High seasonal average LWP values of maize, noted under the T_1 treatment, implied that the plants did not have water stress (Fig. 1) as reported earlier (Kaman *et al.,* 2011; Fig. 3). The LWP under the T_2 and T_3 treatments followed the T_1 treatment. Similar findings were reported earlier by Kirda *et al.* (2005) in their study on maize. Proportionally higher LWP values under the PRD treatment compared to that noted under traditional deficit irrigation practices, were also reported for various other plant species such as; tomato (Zegbe *et al.,* 2004), bean (Wakrim *et al.,* 2005), grape vine (De Souza *et al.,* 2005), olive (Wahbi *et al.,* 2005; Centritto *et al.,* 2005) and pepper (Dorji *et al.,* 2005). High LWP values simply show that the root-zone soil water content is also high (Wanjura and Upchurch, 2002).

In numerous earlier studies, plants' responses were examined under the traditional irrigation practices and PRD technique with the predawn LWP measurements (Zegbe *et al.,* 2004; Centritto *et al.,* 2005; Wahbi *et al.,* 2005; De Souza *et al.,* 2005; Dorji *et al.,* 2005). The predawn LWP measurements for pepper, as reported by Dorji *et al.* (2005) were lower under the T_3 treatment compared to the T_2 treatment. Similar findings were reported for grape vine (De Souza *et al.,* 2005). The data of this study showed that under the T_3 treatment, the P.3394 maize species had low values following the irrigation. In contrast, Rx: 9292 maize species; however, had the lowest LWP value under the T_2 treatment before the irrigation, but increased to the highest value following the irrigation. The species Rx: 9292 had the same LWP values under both T_1 and the traditional deficit irrigation (T_3) treatments. In the second year of the study, the predawn LWP values increased as normally expected following the irrigation (Fig. 6). The Highest LWP values were noted under the T_2 treatment, with 35% water deficit compared to the T_1 treatment. Under the T_3 treatment, similarly 35% water deficit compared to T_1 treatment, the LWP values were the lowest, implying that plants were suffering from water stress under the T_3 treatment. The lower predawn-LWP values observed under the T_3 treatment, compared to the T_2 irrigation practices, were reported by numerous earlier studies (e.g., Zegbe *et al.,* 2004; Centritto *et al.,* 2005; Wahbi *et al.,* 2005; De Souza *et al.,* 2005; Dorji *et al.,* 2005). In other words, the claim that root-leaf signal communication mechanism enables plants to use the already existing water more efficiently seems acceptable (Dry and Loveys, 1998; Mingo *et al.,* 2003; Zegbe-Dominguez *et al.,* 2003). The root-leaf signaling mechanism changes depending on the plant species.

***Conclusions*:** The results of this work showed that the maize cultivars responded rather differently to water stress developed under different techniques of deficit irrigation treatments (i.e., T_2 versus T_3). The findings were supported by leaf-water potential (LWP) measurements, made before and after irrigation. In this context, the relative decrease of crop yields, compared to fully irrigated control treatment, was lower with maize cultivars P.3394, Tector and Tietar under the T_2 treatment compared to that attained with traditional deficit T_3 treatment. The cultivars in question had maintained relatively higher LWP measurements, before irrigation compared to that of T_3 treatment. However, the cultivars Rx:

9292 gave the highest and P.31.G.98 gave the lowest crop yields, under the tested treatments, irrespective of the mode of deficit irrigation (i.e., T_2 or T_3). The yield results, therefore, showed that the crop yield decrease under the deficit irrigation depended largely on the crop cultivars used. Thus, the maize cultivars that give the highest LWP before irrigation may be a good asset for maize breeding for high crop yields under deficit irrigation practices that should be promoted in areas of water scarce-regions.

***Acknowledgments*:** The authors gratefully acknowledge that this work was supported with a research grant through the project ZF2004D2 by Cukurova University. Thanks are due Koseoglu Tarim, May Agro, Monsanto, Pioneer and Syngenta firms for supplying the seeds of different maize cultivars and to Prof. Dr. Ahmet Can Ulger for his help for implementing the field trials. The authors also would like to thank the Research Fund of Akdeniz University for its partial support.

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