International Journal of Plant Production 7 (3), July 2013
ISSN: 1735-6814 (Print), 1735-8043 (Online)
www.ijpp.info

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Growth and physiologic response of rapeseed (*Brassica napus* L.) to deficit irrigation, water salinity and planting method

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Received 19 October 2012 ; Accepted after revision 19 March 2013; Published online 1 April 2013

Abstract

Salinity and water stress reduces the ability of plant to take up water and decrease growth rate, photosynthesis rate (A_n) and stomatal conductance (g_s) of plants. In this study, effects of deficit irrigation with different salinity levels and planting method (in-furrow and on-ridge) as strategies for coping with water and salinity stress on physiologic properties of rapeseed was investigated in a two years experiment. Irrigation treatments consisted of full irrigation (FI) and 0.75FI and 0.50FI in first year and 0.65FI and 0.35FI in second year and salinity treatments of irrigation water were 0.6 (well water), 4.0, 7.0 m and 10.0 dS^{-1} in first year and 0.6, 4.0, 8.0 and 12.0 dSm^{-1} in second year. Planting in-furrow increased seasonal dry matter by 8.4 and 9.6%, respectively at first and second year (with frost occurrence in dormant period in second year) relative to on-ridge planting. In-furrow planting increased maximum leaf area index compared with on-ridge planting by 12.8% for second year. Deficit irrigation and salinity decreased dry matter, leaf area index and had no significant effect on crop growth rate (CGR) and relative growth rate (RGR). Decrease in applied water resulted in lower stomatal conductance (g_s) and photosynthesis rate (A_n) and salinity had no significant effect on these traits. Ratio of photosynthesis rate to transpiration rate (leaf scale transpiration efficiency, A_n/T) decreased when leaf vapor pressure deficit (VPD) increased and in water and salinity stress conditions, transpiration efficiency of rapeseed decreased. A linear function between A_n/T and VPD with negative slope indicated that in higher VPD, A_n/T decreased, therefore in water stress condition or in arid and semi-arid region in comparison with humid region A_n/T of rapeseed decreased. There was no significant difference between the effects of water salinity levels (up to 12 dS m^{-1}) and planting method on slopes of the

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relationships between A_n and g_s and VPD. As forage plant, rapeseed can be cultivated in soils with salinity of 3.4 dS m^{-1} and 11.7% deficit irrigation can be imposed without dry matter reduction and in-furrow planting method was proposed in salinity and water stress conditions in comparison with on-ridge planting.

Keywords: Physiologic properties; Planting method; Rapeseed; Salinity; Water stress.

Introduction

Shortage and salinity of irrigation water are two major parameters that influence physiologic properties of rapeseed. Salinity and water stress reduces the ability of plant to take up water and decrease growth rate, photosynthesis rate (A_n) and stomatal conductance (g_s) of plants (Munns, 2002; Huang and Redmann, 1995; Jensen et al., 1996). Photosynthesis rate is reduced by increase in salinity level as a result of lower stomatal conductance, depression in specific metabolic processes in carbon uptake, inhibition in photochemical capacity, or a combination of these phenomena (Ashraf, 2001). There was positive relationship between A_n and g_s (Ahmadi et al., 2010; Ulfat et al., 2007; Flexas and Medrano, 2002). In addition, genetic variation for A_n and g_s among canola cultivars and highly significant correlation between A_n and g_s emphasizes that A_n and g_s could be used as effective selection criteria for salt tolerance in canola (Ulfat et al., 2007). Effect of deficit irrigation and salinity on A_n and g_s are not similar so that g_s declined more rapidly than A_n under water and salinity stresses (Ahmadi et al., 2010; Flexas and Medrano, 2002). Furthermore, environmental conditions such as vapor pressure deficit between leaf and air can affect A_n and g_s (Addington et al., 2004; Tafteh and Sepaskhah, 2012; Sepaskhah and Tafteh, 2012; Ahmadi et al., 2010).

The decline in leaf growth occurred as earliest response to salinity and water stress in plant that resulted in reduction of growth rate and dry matter production (Cramer, 2002; Bybordi, 2010). Deficit irrigation (Shabani et al., 2009; Shikh et al., 2005; Mandal et al., 2006; Munns, 2002) and salinity (Ashraf and Mc Neilly, 2004; Munns, 2002; Bybordi, 2010) reduced dry matter production and leaf area index of rapeseed. This is important since rapeseed is cultivated as forage crop for livestock (Font et al., 2005; Kirkegaard et al., 2006; Zhang et al., 2007a). Therefore, high water consumptive crops such as maize and alfalfa can be replaced by rapeseed as low water consumptive crop.

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For coping with water scarcity, different procedures are proposed such as: raised bed planting (Kukal et al., 2010), in-furrow planting (Zhang et al., 2007b), deficit irrigation (Sinaki et al., 2007; Istanbulluoglu et al., 2010; Sepaskhah and Ahmadi, 2010; Sepaskhah and Tafteh, 2012; Pirmoradian et al., 2004a; Pirmoradian et al., 2004b; Sepaskhah and Akbari, 2005; Shabani et al., 2010) and identification of drought-resistant varieties (Abbasi and Sepaskhah, 2011a; Abbasi and Sepaskhah, 2011b). Reduction in soil evaporation from in-furrow planting resulted in reduction in water consumption and increase in water productivity (Buttar et al., 2006).

To mitigate the effect of irrigation water salinity on crop growth, several strategies can be used such as: cultivation of resistant varieties to salinity (Ahmadi and Niazi-Ardekani, 2006), leaching the soil salt during or out of the growing season to prevent salt accumulation and cultivation of plant in-furrow (Dong et al., 2010; Zhang et al., 2007b). Furrow irrigation with saline water caused salt accumulation on ridge and decreased soil salinity in furrow (Wadleigh and Fireman, 1949). Better conditions for plant growth are provided by in-furrow planting due to higher soil moisture, higher salt leaching and reduction in evaporation from the soil surface (Zhang et al., 2007b; Li et al., 2010). Reduced soil evaporation and decrease in water requirement for leaching due to low salinity of root zone in-furrow planting resulted in reduced amount of irrigation water. The effects of salinity level of irrigation water and deficit irrigation at different planting methods on rapeseed yield are reported by Shabani et al. (2012). However, their effects on physiologic response of rapeseed are to be evaluated. The objectives of this investigation were to study the effects of deficit irrigation and salinity and planting method (in-furrow and on-ridge) on physiologic response of rapeseed (*Brassica napus* L.) including: dry matter production, crop growth rate, leaf area index, photosynthesis rate, stomatal conductance in a silty clay loam soil under semi-arid climate.

Methods and Materials

This experiment was conducted at the Experimental Research Station in Agricultural College, Shiraz University, I.R. of Iran, in 2009-2010 and 2010-2011 growing seasons. Minimum temperature in November 2009 and 2010 was -5 and -8.6 ^{o}C, respectively. Frost occurred in initial growing stage before plant dormancy initiation in 2010-2011 growing season (Figure 1).

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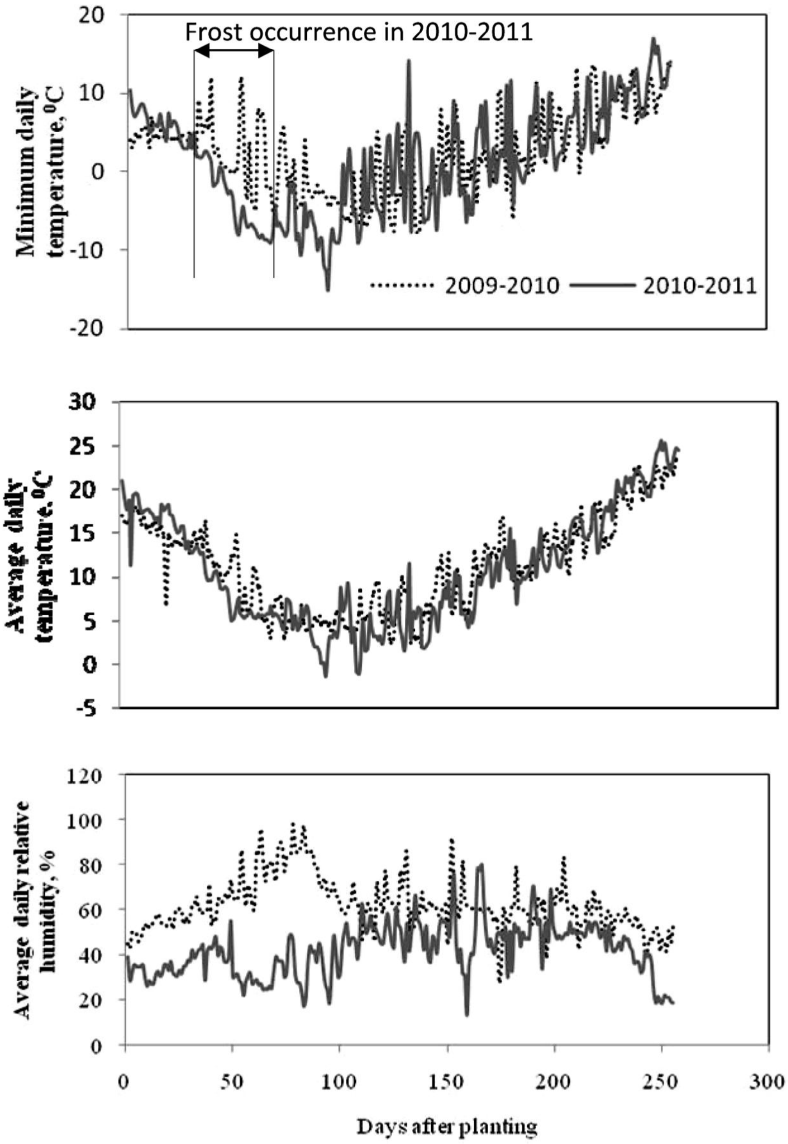

Figure 1. Minimum daily temperature, average daily temperature and average daily relative humidity of air in two years.

Physical and chemical properties of soil and water are shown in Tables 1 and 2. Experimental design was a split-split plot arrangement in randomized complete block design with irrigation treatment as the main plot, salinity

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levels of water as the subplot and planting method as the sup-subplot with three replications. Irrigation treatments were water requirement plus 20% leaching fraction (full irrigation, FI), 75 and 50 percent of full irrigation in first growing season and FI, 65 and 35 percent of full irrigation in second growing season. The salinity treatments of irrigation water were 0.6 (well water), 4.0, 7.0 and 10.0 dS m^{-1} in first growing season and 0.6, 4.0, 8.0 and 12.0 dSm^{-1} in second growing season. The planting methods were on-ridge planting and in-furrow planting. Saline water obtained by addition of NaCl and $CaCl_2$ to the well water with equal proportion. Dimension of each plot was 3×4 m and distance between two adjacent plots was 1.0 m to prevent water invasion from one plot to another. Talaieh cultivar of rapeseed (a local cultivar) was planted on 27 September 2009 and 28 September 2010. Seeds were planted in five rows with spacing between rows of 0.5 m with seed planting rate of 8.0 kg ha^{-1}. Average density of plants was 78 plants per m^2. Before each irrigation, soil water content at different depths of 0.2, 0.3, 0.6, 0.9, 1.2 and 1.5 m was measured with neutron scattering method. Soil water content in the root zone was used to determine the amount of irrigation water as calculated by the following equation:

$$d_n = \sum_{i=1}^{n} \left(\theta_{fci} - \theta_i\right) \Delta z_i \quad (1)$$

Table 1. Soil physical and chemical properties of the experimental site.

Physical properties	Soil depth (cm)				
	0-10	10-30	30-60	60-90	90-120
FC (cm^3 cm^{-3})	0.30	0.32	0.33	0.33	0.33
PWP (cm^3 cm^{-3})	0.16	0.16	0.19	0.19	0.19
ρ_b (g cm^{-3})	1.3	1.43	1.43	1.43	1.43
Clay (%)	35	31	39	34	29
Silt (%)	55	57	51	50	53
Sand (%)	10	12	10	16	18
Soil texture	Silty clay loam				
Chemical properties					
EC (dS m^{-1})	0.65	0.65	0.51	0.58	0.53
Cl (meq l^{-1})	3.22	3.22	1.58	2.35	1.78
Ca (meq l^{-1})	3.36	3.36	2.66	2.98	2.74
Mg (meq l^{-1})	3.68	3.68	3.30	3.48	3.34
Na (meq l^{-1})	1.02	1.02	0.74	0.87	0.77

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Table 2. Chemical analysis of different irrigation water used in the experiment.

Electrical conductivity	Cl	Ca	Na	HCO_3
$dS\ m^{-1}$	$meq\ l^{-1}$			
0.6	2.05	3.80	1.09	5.24
4.0	40.37	39.41	3.03	4.64
7.0	77.98	74.27	4.74	4.10
8.0	91.31	85.89	5.31	3.92
10.0	119.16	109.13	6.45	3.56
12.0	148.59	132.37	7.59	3.20

Where d_n is the irrigation water depth (m), θ_{fci} and θ_i are the volumetric soil water content in layer i at field capacity and before irrigation, respectively ($m^3\ m^{-3}$), Δz is the soil layer thickness (m) and n is the number of soil layers. Depth of root was estimated by the following equation (Borg and Grimes, 1986):

$$Z_r = R_{DM}\left[0.5 + 0.5\sin\left(\frac{3.03D_{as}}{D_{tm}} - 1.47\right)\right] \tag{2}$$

Where Z_r is the root depth (m), R_{DM} is the maximum root depth, 0.9 m, D_{as} is the number of days after planting, D_{tm} is the number of days for maximum root depth, 214 d. Leaching fraction of 20% was applied to prevent salt accumulation in the root zone.

Figures 2 and 3 show the amounts of reference evapotranspiration (ET_0), irrigation water applied for each irrigation event for different irrigation treatments and rainfall for 2009-2010 and 2010-2011, respectively. Triple superphosphate at a rate of 100 kg ha^{-1} and urea as 30% of total requirement (150 kg ha^{-1}) were mixed with the soil at plowing. The remaining urea was applied in spring in two times, i.e., before stem elongation and flowering stage.

Stomatal conductance (g_s) and net photosynthesis rate (A_n) were measured on fair weather days in 51, 95, 148, 175, 214 and 234 days after planting in first year and 194, 208 and 229 days after planting in second year. In second year, stomatal conductance and net photosynthesis rate in autumn were not measured due to frost occurrence and leaf damage. Measurement of g_s and A_n were made using a LC_i analyzer (Li-Cor Inc, Nebraska, USA).

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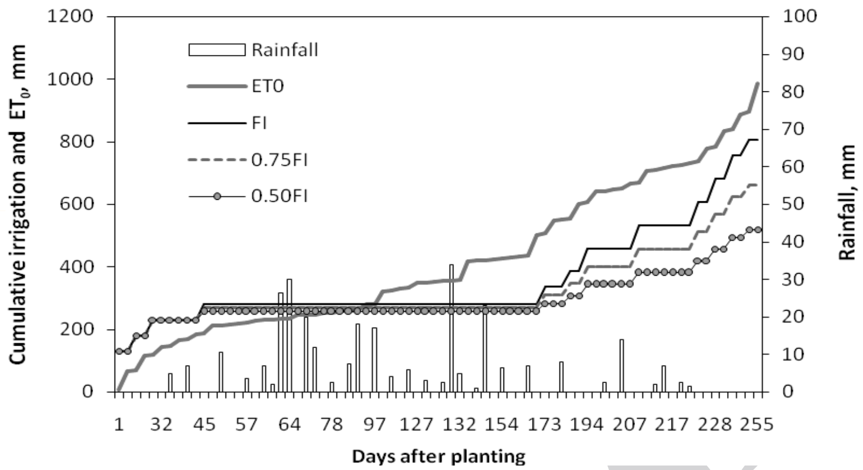

Figure 2. Cumulative reference evapotranspiration (ET_0) and rainfall and applied irrigation (FI, 0.75FI, 0.5FI) water in 2009-2010.

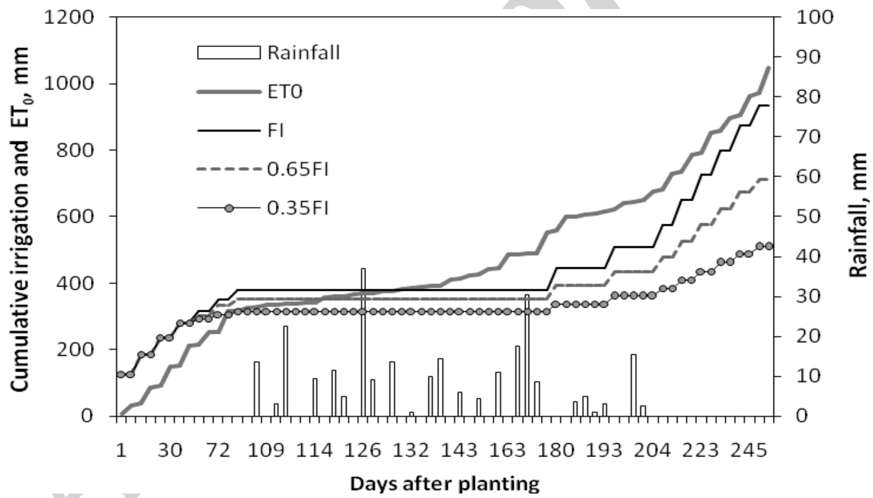

Figure 3. Cumulative reference evapotranspiration (ET_0) and rainfall and applied irrigation (FI, 0.65FI, 0.35FI) water in 2010-2011.

To assess the soil salinity in the root zone soil samples were taken in 0.3 m increment to depth of 1.2 m in two replications. Salinity of saturated soil extract was measured as described by the U.S. Salinity Laboratory Staff (USDA, 1954).

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Micro-lysimeter was used to measure evaporation (E) from the soil surface. One small cylinder with dimensions of 9 cm diameter and 30 cm height that filled with the same field soil was buried in the surface soil. The micro-lysimeter was weighted between irrigation intervals to determine the soil evaporation.

Shape of rapeseed leaves in fall and winter was different from those in spring. Relationships between leaf area and its dimensions were determined by the following equations (Figure 4):

$$LA_f = 0.589(W \times L) + 2.801 \quad R^2=0.969 \tag{3}$$

$$LA_s = 0.792(W \times L) + 1.355 \quad R^2=0.920 \tag{4}$$

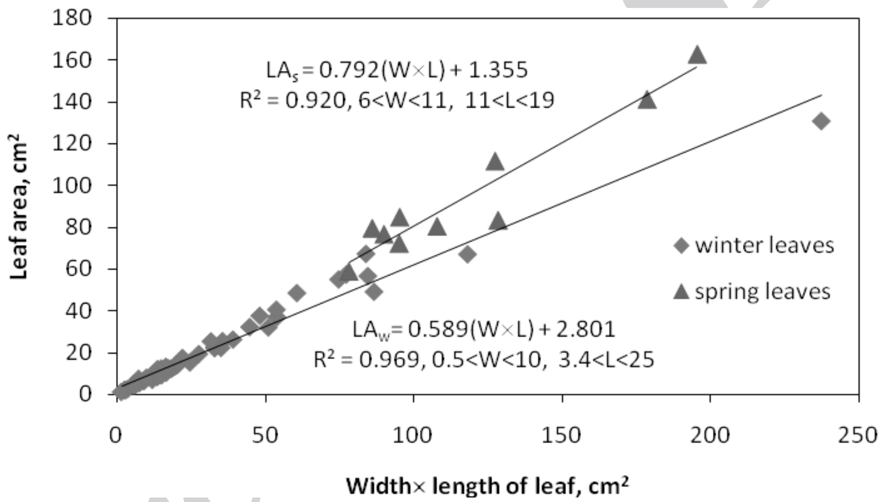

Figure 4. Relationships between leaf area and its dimensions.

Where LA_f and LA_s are leaf area in fall and spring (cm^2), respectively and W is the leaf width (cm) and L is the leaf length (cm). To determine leaf area index (LAI), three plants were selected from each plot and area of their leaves were determined by Eq. (3) and (4). LAI was determined in 52, 149, 178, 217, 231 and 243 days after planting in 2009-2010 and 41, 100, 186, 207, 228 and 247 days after planting in 2010-2011. To determine dry matter, the samples that were taken for LAI measurement were dried at 70 ^{o}C for 72 h and weighted.

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On the basis of dry matter accumulation, the values for crop growth rate (CGR) and relative growth rate (RGR) were calculated by the following equations (Zhao et al., 2007):

$$CGR=(W_2 - W_1)/(T_2 - T_1) \quad (5)$$

$$RGR=(1/W)dW/dt= (lnW_2 - lnW_1)/(T_2 - T_1) \quad (6)$$

Where W_1 and W_2 are dry matter in g m^{-2} at times T_1 and T_2 (in days).

Vapor pressure deficit (VPD) between leaf and air was calculated by the following equation:

$$VPD= e_s - e_a \quad (7)$$

Where e_s is the saturation vapor pressure (kPa) at the leaf temperature and e_a is the actual water vapor pressure (kPa) at the outside air. In Eq. (7), it is assumed that air is saturated within stomata. Saturated vapor pressure at the leaf and air was calculated by the following equation (Allen, 2005):

$$e_s = 0.611 \exp\left(\frac{17.27T}{T + 237.3}\right) \quad (8)$$

Where T is the air temperature in and out of the leaf. Actual vapor pressure at the outside air was calculated by the following equation:

$$e_a = RH \times e_s \quad (9)$$

Where RH is the outside air relative humidity.

Results and Discussion

Soil water depth

Soil water depths of root zone before last irrigation are shown in Table 3. In two years, there were no distinct difference between soil water depth of root zone in different salinity levels. With decrease in applied water, soil water depth decreased. Soil water depth was higher in-furrow planting method compared with those on-ridge planting due to leaves shading on the wetted surface area of furrow and less evaporation from its soil surface.

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Table 3. Soil water depth in root zone for two years.

year	Irrigation treatment	Planting method							
		On-ridge planting				In-furrow planting			
Soil water depth, mm									
		Irrigation water salinity, dS m^{-1}							
		0.6	4.0	7.0	10.0	0.6	4.0	7.0	10.0
2009-10	Full irrigation (FI)	193	195	197	194	198	200	203	194
	0.75FI	178	179	186	190	184	191	195	185
	0.5FI	150	147	158	155	155	151	168	176
		Irrigation water salinity, dS m^{-1}							
		0.6	4.0	8.0	12.0	0.6	4.0	8.0	12.0
2010-2011	FI	194	192	196	197	192	189	196	197
	0.65FI	167	161	165	170	168	166	168	171
	0.35FI	140	145	158	146	145	162	140	156

Evaporation

Evaporation from soil surface between two irrigation intervals is shown in Table 4. In two years, with decrease in applied water in irrigation treatment, evaporation decreased. In second year in comparison with first year, evaporation was higher due to lower air relative humidity (Figure 1) and more reference evapotranspiration (Figures 2 and 3). In two years, there was no distinct difference between evaporation from soil surface in different salinity levels.

Table 4. Mean values of evaporation from soil surface (mm) between two irrigation interval for two years.

	2009-2010									2010-2011							
	Days after planting																
	180		202		235		241			192		213		238		246	
	Salinity levels, dS m^{-1}																
	0.6	10.0	0.6	10.0	0.6	10.0	0.6	10.0		0.6	12.0	0.6	12.0	0.6	12.0	0.6	12.0
Irrigation** treatment									Irrigation treatment								
FI	7.6	7.9	10.8	11.8	11.3	11.5	15.0	14.0	FI	14.2	14.7	12.1	12.6	12.9	17.5	16.8	28.9
0.75FI	6.3	7.2	10.1	9.4	11.1	10.8	11.0	12.0	0.65FI	13.3	11.0	10.1	9.2	10.9	15.7	18.5	18.4
0.50FI	8.3	7.2	7.8	7.9	9.3	8.0	10.0	12.0	0.35FI	10.0	7.9	6.4	6.4	8.7	9.8	11.0	11.0

** FI: Full irrigation.

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Dry matter

There was significant effect of deficit irrigation in first year, salinity in second year and planting method in two years on top dry matter (DM) at the end of rain season and beginning of treatment. With exception of measurement at 228 days after planting in first year and 207 days after planting in second year, deficit irrigation in second year and salinity in first year had no significant effect on DM (Table 5). Relationship between percent of dry matter reduction and ratio of deficit irrigation determined by regression analysis is shown in Figure 5. Results indicated that 11.7% deficit irrigation can be imposed without dry matter reduction. Relationship between relative dry matter and soil saturation extract salinity was determined by regression analysis as follows (Figure 6):

$$(DM_a/DM_m) = 1\text{-}0.028\ (EC_e\text{-}3.43),\ R^2=0.631 \qquad (10)$$

Table 5. Mean values of top dry matter (Mg ha^{-1}) in each irrigation, water salinity and planting methods treatments for two years.

	Days after planting												
	2009-2010							2010-2011					
	52	149	178	215	228	255		41	100	186	207	228	255
Irrigation treatment**							Irrigation treatment						
FI	1.2^{a*}	2.3^{a}	4.30^{a}	8.3^{a}	9.4^{a}	9.8^{a}	FI	1.3^{a}	0.5^{a}	2.4^{a}	5.4^{a}	8.2^{a}	8.5^{a}
0.75FI	0.7^{a}	1.9^{a}	4.05^{a}	7.7^{b}	8.5^{b}	8.9^{ab}	0.65FI	1.2^{a}	0.5^{a}	1.8^{a}	4.7^{b}	7.1^{a}	7.4^{a}
0.50FI	1.0^{a}	1.6^{a}	3.50^{b}	6.5^{c}	7.1^{c}	7.4^{b}	0.35FI	1.4^{a}	0.4^{a}	2.0^{a}	4.3^{c}	6.7^{a}	6.9^{a}
Salinity levels dS m^{-1}							Salinity levels dS m^{-1}						
0.6	0.9^{a}	2.0^{a}	4.20^{a}	7.8^{a}	8.6^{a}	9.0^{a}	0.6	1.2^{a}	0.4^{a}	2.2^{a}	5.0^{a}	7.6^{a}	8.0^{a}
4.0	1.0^{a}	2.1^{a}	4.04^{a}	7.6^{a}	8.5^{a}	9.0^{a}	4.0	1.2^{a}	0.4^{a}	2.2^{a}	5.2^{a}	7.8^{a}	8.1^{a}
7.0	0.9^{a}	1.9^{a}	3.86^{a}	7.3^{a}	8.1^{b}	8.4^{a}	8.0	1.4^{a}	0.5^{a}	2.1^{a}	4.7^{b}	7.2^{ab}	7.5^{ab}
10.0	1.1^{a}	1.7^{a}	3.70^{a}	7.4^{a}	8.1^{ab}	8.4^{a}	12.0	1.4^{a}	0.5^{a}	1.9^{a}	4.3^{c}	6.8^{b}	6.9^{b}
Planting method							Planting method						
On-ridge	0.9^{a}	1.8^{a}	3.9^{a}	7.2^{a}	8.0^{a}	8.3^{a}	On-ridge	1.4^{a}	0.4^{a}	1.7^{a}	4.2^{a}	7.0^{a}	7.3^{a}
In-furrow	1.0^{a}	2.0^{a}	4.04^{a}	7.9^{b}	8.6^{b}	9.0^{b}	In-furrow	1.2^{a}	0.5^{a}	2.4^{b}	5.4^{b}	7.7^{b}	8.0^{b}

[*] Mean followed by the same letters in columns for each factor and each trait are not significantly different at 5% level of probability, using Duncan multiple rang test.
[**] FI: Full irrigation.

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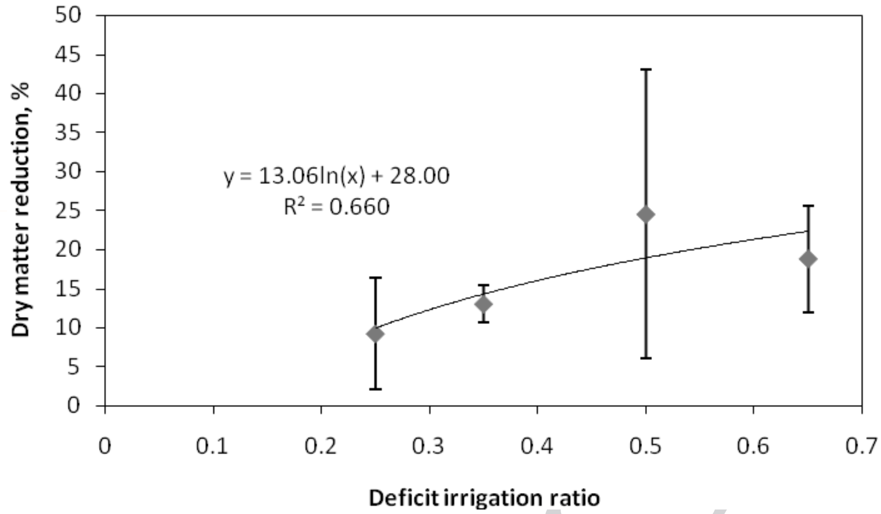

Figure 5. Relationship between dry matter reduction and ratio of deficit irrigation.

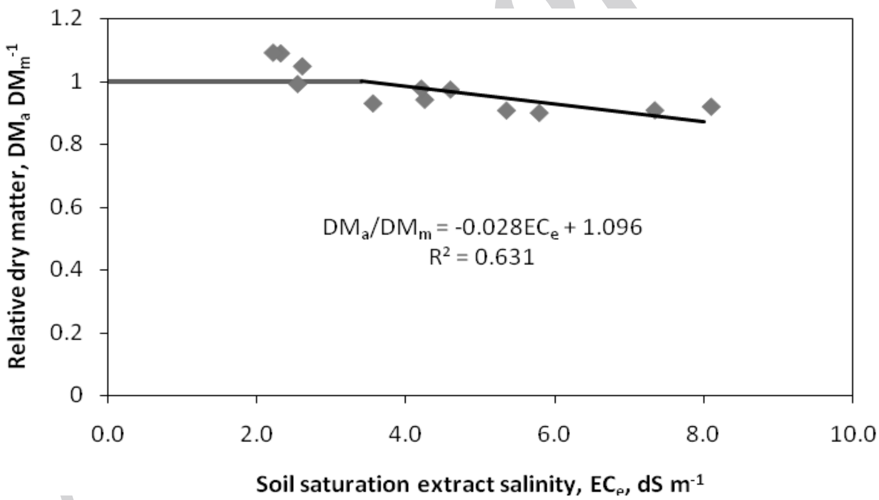

Figure 6. Relationship between relative dry matter and soil saturation extract salinity.

Where DM_a and DM_m are the actual and maximum dry matter, respectively and EC_e is the soil saturation extract salinity in dS m^{-1}. The value of 3.43 is the EC_e threshold for DM. The coefficient in Eq. (10) indicated a reduction of DM per unit soil saturation extract salinity as 2.8%

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per 1 dS m^{-1}. Dry matter reduction occurred for salinity higher than 3.43 dS m^{-1}. Therefore, rapeseed can be cultivated as forage crop in salinity conditions. In second year due to frost occurrence in fall, DM in 100 days after planting decreased. There was no significant difference in DM in different irrigation treatments in second year. However, DM was higher in full irrigation treatment by 25% in comparison with 0.5FI. Furthermore, DM was higher in-furrow planting in comparison with on-ridge planting method (25%). Higher DM in full irrigation treatment and in-furrow planting method is due to higher soil water content (Table 3) in these treatments. Higher soil water content resulted in reduction of reflection coefficient (albedo) and increased soil heat conductivity and specific heat capacity so that temperature variant of soil surface diminished (Alkhaier et al., 2009). Therefore, in areas with frost occurrence in fall, strategies such as adequate irrigation and in-furrow planting are beneficial and deficit irrigation is not appropriate before beginning of dormant period. In last measurement, at different water salinity levels and planting methods, deficit irrigation resulted in decrease in DM by 9.2 and 24.5% for 0.75FI and 0.50FI, respectively in first year and by 13 and 18.8% for 0.65FI and 0.35FI, respectively in second year in comparison with full irrigation. Dry matter decreased in second year in comparison with first year, due to frost occurrence at initial vegetative stage of growth. Dry matter was increased in in-furrow planting compared with on-ridge planting by 8.4 and 9.6% for first and second year, respectively. Therefore, when forage production is the aim of rapeseed planting, in-furrow planting method was proposed in salinity and water stress conditions. There was no significant interaction effect between deficit irrigation and salinity and planting method on DM at different years (data not presented).

Leaf area index

There was significant effect of deficit irrigation and planting method on Leaf Area Index (LAI) in second year and salinity had no significant effect on LAI in two years (Table 6). In second year due to frost occurrence in fall, LAI in 100 days after planting decreased. There was no significant difference in LAI in different irrigation treatments in second year. However, LAI was higher in full irrigation treatment. Furthermore, LAI was higher in-furrow planting in comparison with on-ridge planting method. Higher LAI in full irrigation treatment and in-furrow planting method is due to higher

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soil water content in these treatments and its effects on soil thermal conditions as concluded in dry matter section. In-furrow planting resulted in increasing maximum LAI by 12.8% in second year in comparison with that obtained by on-ridge planting. There was no significant interaction effect between deficit irrigation and salinity and planting method on LAI at different growing seasons (data not presented).

Table 6. Mean values of leaf area index in each irrigation, water salinity and planting methods treatments for two years.

	Days after planting												
	2009-2010							2010-2011					
	52	149	178	217	231	243		41	100	186	207	228	247
Irrigation treatment**							Irrigation treatment						
FI	1.31^{a*}	3.38^{a}	5.72^{a}	5.3^{a}	3.63^{a}	0.45^{a}	FI	1.05^{a}	0.34^{a}	3.37^{a}	5.38^{a}	2.5^{a}	0.93^{a}
0.75FI	1.26^{a}	3.76^{a}	5.77^{a}	5.06^{a}	2.97^{a}	0.39^{a}	0.65FI	1.03^{a}	0.28^{a}	3.36^{a}	4.72^{c}	2.12^{c}	0.57^{b}
0.50FI	1.22^{a}	3.69^{a}	5.79^{a}	5.17^{a}	2.47^{a}	0.08^{a}	0.35FI	0.89^{a}	0.17^{a}	2.92^{a}	4.9^{b}	2.21^{b}	0.45^{b}
Salinity levels dS m^{-1}							Salinity levels dS m^{-1}						
0.6	1.23^{a}	3.87^{a}	5.82^{a}	5.18^{a}	2.97^{a}	0.33^{a}	0.6	1.02^{a}	0.27^{a}	3.1^{a}	5.2^{a}	2.36^{a}	0.71^{a}
4.0	1.29^{a}	3.64^{ab}	5.79^{a}	5.29^{a}	3.17^{a}	0.41^{a}	4.0	0.91^{a}	0.27^{a}	3.25^{a}	4.8^{a}	2.14^{b}	0.72^{a}
7.0	1.19^{a}	3.32^{a}	5.72^{a}	5.22^{a}	3.0^{a}	0.27^{a}	8.0	0.91^{a}	0.26^{a}	3.17^{a}	5.0^{a}	2.35^{a}	0.60^{a}
10.0	1.35^{a}	3.62^{ab}	5.72^{a}	5.05^{a}	2.95^{a}	0.25^{a}	12.0	1.12^{a}	0.28^{a}	3.35^{a}	4.98^{a}	2.21^{ab}	0.56^{a}
Planting method							Planting method						
On-ridge	1.26^{a}	3.49^{a}	5.79^{a}	5.03^{a}	2.95^{a}	0.34^{a}	On-ridge	1.1^{a}	0.18^{a}	3.11^{a}	4.7^{a}	2.11^{a}	0.58^{a}
In-furrow	1.27^{a}	3.72^{a}	5.73^{a}	5.34^{a}	3.1^{b}	0.29^{a}	In-furrow	0.93^{a}	0.35^{b}	3.33^{b}	5.3^{b}	2.42^{b}	0.71^{b}

* Mean followed by the same letters in columns for each factor and each trait are not significantly different at 5% level of probability, using Duncan multiple rang test.
** FI: Full irrigation.

Crop growth rates

Crop growth rate (CGR) and relative growth rate (RGR) for two years was calculated by Eqs. (5) and (6) (Tables 7 and 8). Variations of CGR and RGR during growing season are dependent on soil, water and weather conditions and plant growth stage so that in initial growth stage (fall) CGR and RGR were high and they reduced in winter. However, by warming the weather in spring the CGR and RGR increased. As a result of leaves senescence and decrease in leaf area index, CGR and RGR decreased at the end of growing season due to reduction of leaf area index and photosynthesis rate. Except with CGR and RGR in 100 days after planting

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in second year, there was no significant difference between the effects of deficit irrigation and salinity on CGR and RGR. Nevertheless, by applied water reduction and enhancement of salinity levels during the growing season, CGR and RGR decreased that resulted in decrease in dry matter at harvest. In some times during the growing season, planting methods had significant effect on the CGR and RGR in two years. In on-ridge planting method, CGR and RGR was lower than those in-furrow planting method. Results indicated that in-furrow planting resulted in increase in CGR by 15.7% in 215 days after planting for first year and 53.3% and 17.6% in 186 and 207 days after planting, respectively, for second year. RGR increased in in-furrow planting by 18.7% in 186 days after planting in second year relative to those obtained in on-ridge planting method. Negative values of CGR and RGR occurred due to frost occurrence in fall in second year that resulted in decrease in dry matter. However, these reductions in full irrigation treatment and in-furrow planting method were lower as concluded for dry matter reduction. For both traits (CGR and RGR), there was no significant interaction effect between deficit irrigation, water salinity and planting method (I×S×P) in first and second year (data not presented).

Table 7. Mean values of crop growth rate (g m^{-2} d^{-1}) in each irrigation, water salinity and planting methods treatments for two years.

	Days after planting												
	2009-2010							2010-2011					
	52	149	178	215	228	255		41	100	186	207	228	255
Irrigation** treatment							Irrigation treatment						
FI	2.3a*	1.1a	7.0a	10.9a	8.0a	1.4a	FI	3.1a	-1.3a	2.3a	14.2a	13.1a	1.4a
0.75FI	1.4a	1.2a	7.5a	9.8a	6.5a	1.4a	0.65FI	3.0a	-1.3a	1.6a	13.5a	11.4a	1.3a
0.50FI	1.8a	0.7a	6.4a	8.1a	4.7a	0.9a	0.35FI	3.4a	-1.7b	1.8a	11.2a	12.0a	0.1a
Salinity levels dS m^{-1}							Salinity levels dS m^{-1}						
0.6	1.8a	1.2a	7.4a	9.6a	6.4a	1.4a	0.6	2.8a	-1.2a	2.0a	13.7a	12.3a	1.3a
4.0	1.9a	1.1a	6.9a	9.6a	7.4a	1.3a	4.0	3.0a	-1.3ab	2.0a	14.1a	12.6a	1.2a
7.0	1.7a	1.1a	6.7a	9.3a	5.7a	1.3a	8.0	3.5a	-1.6c	1.9a	12.4a	12.1a	0.8a
10.0	1.9a	0.7a	6.9a	9.9a	6.0a	1.1a	12.0	3.4a	-1.6bc	1.7a	11.7a	11.7a	0.6a
Planting method							Planting method						
On-ridge	1.8a	1.0a	6.9a	8.9a	6.7a	1.1a	On-ridge	3.4a	-1.6a	1.5a	11.9a	13.2b	0.9a
In-furrow	1.9a	1.1a	7.0a	10.3b	6.1a	1.4a	In-furrow	2.9a	-1.3a	2.3b	14.0b	11.2a	1.0a

[*] Mean followed by the same letters in columns for each factor and each trait are not significantly different at 5% level of probability, using Duncan multiple rang test.
[**] FI: Full irrigation.

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Table 8. Mean values of relative growth rate $\times 10^2$ (d^{-1}) in each irrigation, water salinity and planting methods treatments for two years.

	Days after planting												
	2009-2010							2010-2011					
	52	149	178	215	228	255		41	100	186	207	228	255
Irrigation treatment[**]							Irrigation treatment						
FI	9.5^{a*}	0.7^{a}	2.3^{a}	1.8^{a}	0.9^{a}	0.1^{a}	FI	12.2	-1.6^{a}	1.8	4.1^{a}	2.0^{a}	0.2^{a}
0.75FI	8.5^{a}	1.0^{a}	2.8^{a}	1.7^{a}	0.8^{a}	0.1^{a}	0.65FI	12.0	-1.6^{a}	1.6	4.7^{a}	2.0^{a}	0.2^{a}
0.50FI	8.8^{a}	0.7^{a}	2.9^{a}	1.7^{a}	0.7^{a}	0.1^{a}	0.35FI	12.4	-2.1^{b}	1.8	4.3^{a}	2.2^{a}	0.0^{a}
Salinity levels dS m^{-1}							Salinity levels dS m^{-1}						
0.6	8.8^{a}	1.0^{a}	2.7^{a}	1.7^{a}	0.8^{a}	0.1^{a}	0.6	12.0	-1.6^{a}	1.8	4.4^{a}	2.0^{a}	0.2^{a}
4.0	9.1^{a}	0.8^{a}	2.5^{a}	1.7^{a}	0.9^{a}	0.1^{a}	4.0	12.0	-1.6^{a}	1.7	4.8^{a}	2.0^{a}	0.2^{a}
7.0	8.8a	0.9^{a}	2.6^{a}	1.7^{a}	0.7^{a}	0.1^{a}	8.0	12.5	-1.9^{a}	1.7	4.1^{a}	2.1^{a}	0.1^{a}
10.0	9.0^{a}	0.6^{a}	2.9^{a}	1.9^{a}	0.8^{a}	0.1^{a}	12.0	12.3	-1.8^{a}	1.6	4.2^{a}	2.2^{a}	0.1^{a}
Planting method							Planting method						
On-ridge	8.8^{a}	0.88^{a}	2.7^{a}	1.7^{a}	0.9^{a}	0.1^{a}	On-ridge	12.4	-2.0^{a}	1.6^{a}	4.6^{a}	2.4^{a}	0.1^{a}
In-furrow	9.0^{a}	0.8^{a}	2.6^{a}	1.8^{a}	0.7^{a}	0.1^{a}	In-furrow	12.0	-1.5^{a}	1.9^{b}	4.1^{a}	1.7^{b}	0.1^{a}

[*] Mean followed by the same letters in columns for each factor and each trait are not significantly different at 5% level of probability, using Duncan multiple rang test.
[**] FI: Full irrigation.

Relationship between crop growth rates and LAI

Figures 7 and 8 shows the global relationship between CGR and RGR and LAI. Dry matter accumulation depends on photosynthesis rate and leaf area. In spring, after warming of weather and increasing LAI, CGR and RGR increased and this relationship is not linear. In high LAI, CGR and RGR rapidly increased. When LAI is equal to zero there occurred slight amount of growth rates (CGR and RGR are 0.924 g m^{-2} d^{-1} and 0.001 d^{-1}, respectively) as intercept of the equation. This small intercept occurred due to large variation in the data point (Figures 7 and 8). The close relationship between RGR and CGR and LAI is due to this fact photosynthesis and dry matter accumulation is strongly dependent on leaf area.

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Photosynthesis and stomatal conductance

Photosynthesis rates (A_n in µmol m^{-2} s^{-1}) and stomatal conductance (g_s in mol m^{-2} s^{-1}) at three different days after planting of rapeseed in spring are shown in Table 9. Before spring there was no significant difference between the effect of deficit irrigation, salinity and planting methods on A_n (data not presented). Results indicated that with exception of measurement at 207 days after planting in second year, there was no significant difference between A_n at different salinity levels. At beginning of spring, due to high soil water content there was no significant difference between the effect of different applied water on A_n, however with intensified deficit irrigation and reduction of soil water content, decrease in photosynthesis rates occurred. There was no significant interaction effect between deficit irrigation, salinity and planting methods on A_n at different times of measurement during the growing season (data not presented). A decreasing trend in A_n from beginning to the end of growing season was observed. Similar results were reported by Ahmadi et al. (2010) for potato.

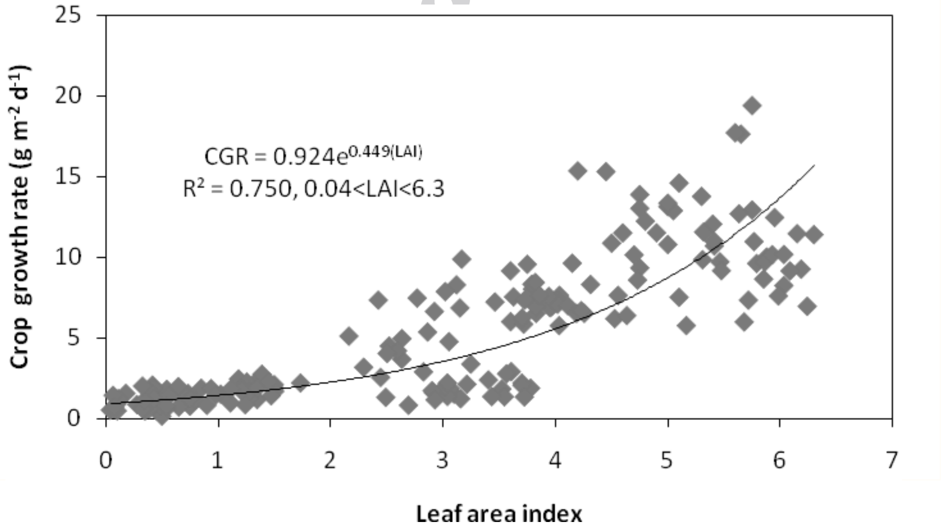

Figure 7. Relationship between crop growth rate (CGR) and leaf area index (LAI) for data obtained in two years after beginning of treatments.

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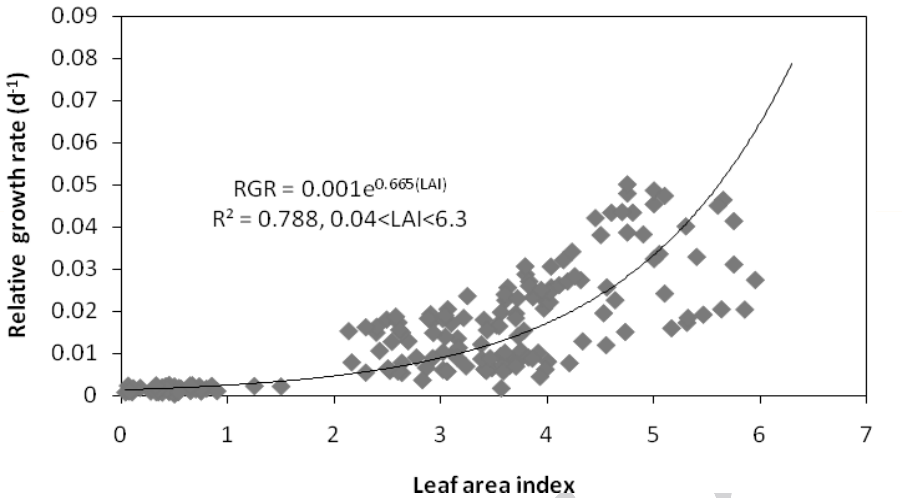

Figure 8. Relationship between relative growth rate (RGR) and leaf area index (LAI) for data obtained in two years after beginning of treatments.

Table 9. Mean values of photosynthesis (A_n in µmol m^{-2} s^{-1}) and stomatal conductance (g_s in mol m^{-2} s^{-1}) in each irrigation, water salinity, and planting methods treatments for two years.

	Days after planting												
	2009-2010							2010-2011					
	175		214		234			194		208		229	
	A_n*	g_s	A_n	g_s	A_n	g_s		A_n	g_s	A_n	g_s	A_n	g_s
Irrigation** treatment							Irrigation treatment						
FI	14.9^{a}	0.19^{a}	16.4^{a}	0.15^{a}	9.5^{a}	0.11^{a}	FI	16.6^{a}	0.17^{a}	11.4^{a}	0.13^{a}	12.2^{a}	0.12^{a}
0.75FI	16.7^{a}	0.21^{a}	13.0^{b}	0.12^{b}	8.2^{a}	0.09^{b}	0.65FI	15.9^{a}	0.16^{a}	10.8^{a}	0.12^{a}	11.7^{b}	0.12^{a}
0.50FI	15.4^{a}	0.20^{a}	12.1^{b}	0.11^{b}	---	---	0.35FI	15.4^{a}	0.15^{b}	9.8^{b}	0.11^{a}	7.5^{c}	0.08^{b}
Salinity levels dS m^{-1}							Salinity levels dS m^{-1}						
0.6	15.8^{a}	0.20^{a}	14.4^{a}	0.13^{a}	8.1^{a}	0.10^{ab}	0.6	16.6^{a}	0.17^{a}	11.7^{a}	0.13^{a}	10.8^{a}	0.11^{a}
4.0	14.5^{a}	0.19^{a}	14.7^{a}	0.13^{a}	9.3^{a}	0.11^{b}	4.0	16.6^{a}	0.17^{a}	10.8^{a}	0.12^{a}	10.7^{a}	0.11^{a}
7.0	15.8^{a}	0.20^{a}	13.35^{a}	0.12^{a}	8.8^{a}	0.10^{b}	8.0	15.5^{a}	0.16^{a}	10.7^{a}	0.12^{a}	10.3^{a}	0.11^{a}
10.0	16.7^{a}	0.22^{a}	13.0^{a}	0.12^{a}	9.1^{a}	0.09^{a}	12.0	15.3^{a}	0.15^{a}	9.5^{b}	0.11^{a}	10.1^{a}	0.10^{a}
Planting method							Planting method						
On-ridge	13.5^{a}	0.18^{a}	14.0^{a}	0.13^{a}	8.6^{a}	0.10^{a}	On-ridge	15.8^{a}	0.16^{a}	10.4^{a}	0.12^{a}	10.3^{a}	0.11^{a}
In-furrow	17.8^{b}	0.23^{b}	13.7^{a}	0.13^{a}	9.2^{a}	0.10^{a}	In-furrow	16.2^{a}	0.15^{a}	11.5^{a}	0.12^{a}	10.7^{a}	0.11^{a}

* Mean followed by the same letters in columns for each factor and each trait are not significantly different at 5% level of probability, using Duncan multiple rang test.

** FI: Full irrigation.

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There was no significant difference between the effects of different salinity levels on g_s. There was a decreasing trend in g_s from beginning to the end of the growing season. Except with measurement at 175 days after planting in first year, there was no significant difference between effect of different planting methods on A_n and g_s. However, in on-ridge planting method, A_n and g_s was lower or equal to those in-furrow planting method. In first year without frost occurrence, planting in-furrow increased A_n and g_s by 31.9 and 27.8%, respectively, at initial growth stage in comparison with on-ridge planting method and in other growth stages significant difference was not observed. Decrease in applied water and soil water content resulted in lower stomatal conductance. Figure 9 shows global relationship between A_n and g_s. With increasing g_s, A_n was increased and this relationship is not linear. In higher stomatal conductance, the rate of increase in photosynthesis was lower. Therefore, in low water stress conditions that resulted in higher stomatal conductance the photosynthesis rate and accumulation of dry matter and seed yield reduced slightly so that the reduction of dry matter accumulation was lower than that for transpiration. That is the basis of deficit irrigation strategies. To assess the effects of deficit irrigation, salinity and planting methods on relationships between A_n and g_s, these relationships were determined separately for each treatment (Table 10 and Figures 10-12). For comparison between two exponential lines, natural logarithm transformation was used to convert these relationships to linear form. Slope and intercepts of lines was compared by statistical F-test. Results indicated that there was no significant difference between the effect of deficit irrigation and planting methods on relationships between A_n and g_s and salinity had significant effect on these relationships (Table 10). In salinity of 0.6 and 4.0 dS m^{-1}, A_n was not prohibited when g_s was equal to 0.0. On the other hand, there was a threshold for g_s in high salinity (10 and 12 dS m^{-1}) so that A_n was zero when g_s was equal to 0.037 mol m^{-2} s^{-1}. Therefore, high salinity resulted in a threshold of g_s for prohibiting the A_n (Figure 11). In no water and salt stress conditions and high stomatal conductance, A_n in in-furrow planting was higher in comparison with on-ridge planting methods.

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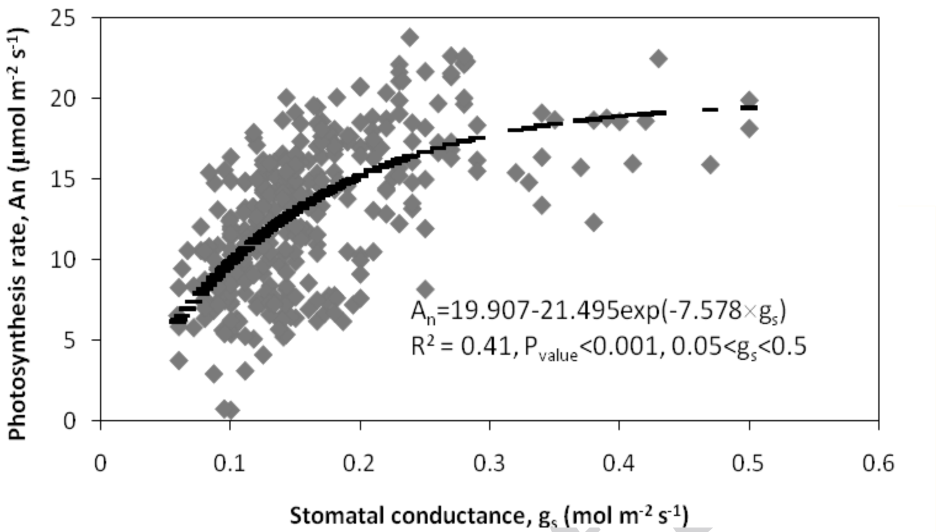

Figure 9. Relationship between photosynthesis rate (A_n) and stomatal conductance (g_s) for all data obtained in two years.

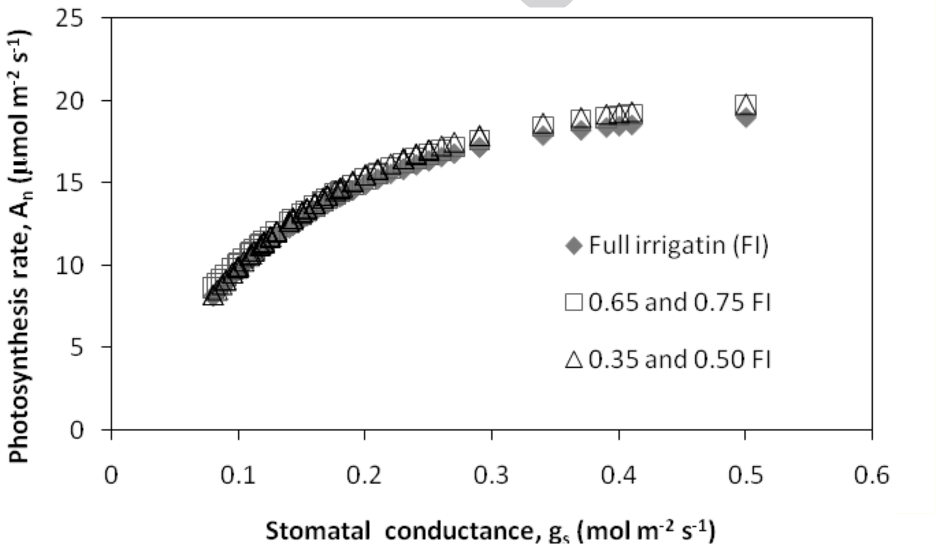

Figure 10. Relationship between photosynthesis rate (A_n) and stomatal conductance (g_s) for different irrigation treatments.

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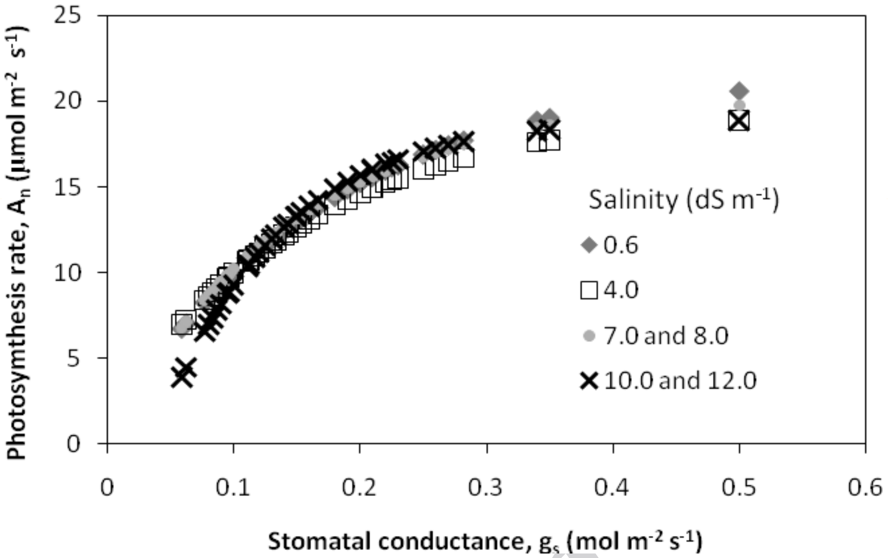

Figure 11. Relationship between photosynthesis rate (A_n) and stomatal conductance (g_s) for different salinity levels.

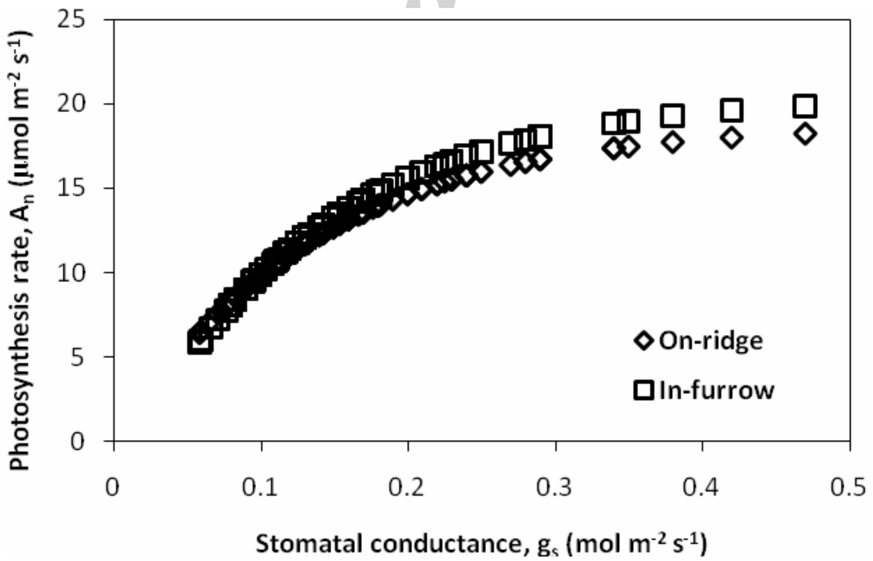

Figure 12. Relationship between photosynthesis rate (A_n) and stomatal conductance (g_s) for different planting methods.

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Table 10. Relationship between photosynthesis rate (A_n in µmol m^{-2} s^{-1}) and stomatal conductance (g_s in mol m^{-2} s^{-1}) in each irrigation, water salinity and planting methods treatments for two years.

Irrigation treatment	equation	R^2	Significant
FI**	A_n=19.403-20.829×exp(-7.653g_s)	0.32	a*
0.65 and 0.75FI	A_n=20.392-20.349×exp(-6.875g_s)	0.40	a
0.35 and 0.50FI	A_n=20.308-22.790×exp(-7.694g_s)	0.47	a
Salinity levels dS m^{-1}			
0.6	A_n=21.671-21.269×exp(-5.982g_s)	0.39	a
4.0	A_n=19.584-18.698×exp(-6.623g_s)	0.32	b
7.0 and 8.0	A_n=20.356-20.469×exp(-6.933g_s)	0.42	c
10.0 and 12.0	A_n=19.044-28.377×exp(-10.682g_s)	0.47	d
Planting method			
On-ridge	A_n=18.726-19.529×exp(-7.837g_s)	0.36	a
In-furrow	A_n=20.505-23.126×exp(-7.783g_s)	0.45	a

* Same letters in columns for each factor are not significantly different at 5% level of probability.
** FI: Full irrigation.

Relationship between A_n, g_s and vapor pressure deficit

Stomata generally close as vapor pressure deficit (VPD) between leaf and the outside air increases. Therefore, A_n and g_s decreased as VPD increase (Figures 13 and 14). Slope of this relationship reflects the sensitivity of the response (Addington et al., 2004). Figure 15 shows the relationship between photosynthesis and transpiration ratio (A_n/T) and VPD. Ratio of A_n/T is water use efficiency or transpiration efficiency at leaf scale in plant. A linear function between A_n/T and VPD with negative slope indicated that in higher VPD, transpiration efficiency decreased, therefore in water stress condition or in arid and semi-arid region in comparison with humid region, transpiration efficiency of rapeseed decreased. Similar results were reported by Ahmadi et al. (2010) for potato and Abbate et al. (2004) for wheat. To assess the effects of deficit irrigation, salinity and planting methods on relationships between A_n, g_s and A_n/T and VPD these relationships were determined separately for different treatments (Table 11). Slope and intercepts of lines compared statistically by F-test. Results indicated that deficit irrigation had significant effect on slope of the fitted line between A_n and g_s and VPD. In maximum water stress (0.35FI and 0.5 FI) relative to full irrigation, the reduction rate of A_n and g_s per each kPa increase in VPD increased by 65.0 and 90.0%, respectively. There was no significant

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difference between the effects of salinity and planting methods on slopes of relationships between A_n and g_s and VPD. However, the rate of decrease in A_n and g_s per each kPa increase in VPD in on-ridge planting was higher than that in in-furrow planting. The rate of decrease in transpiration efficiency per each kPa increase in VPD was not affected by deficit irrigation and salinity and planting methods. Therefore, this rate was 0.610 g kg^{-1} kPa^{-1} that obtained from all data (Figure 15). This value was lower than 1.63 g kg^{-1} kPa^{-1} (average value) that reported by Ahmadi et al. (2010) for potato. Therefore, rapeseed was more tolerant to VPD variation in comparison with potato. So this index is a beneficial tool to compare the crops and cultivars to VPD variations.

Conclusions

In in-furrow planting, leaf area index, dry matter, photosynthesis rate (A_n) and stomata conductance (g_s) were higher in comparison with on-ridge planting method. Deficit irrigation and salinity decreased dry matter, leaf area index and had no significant effect on crop growth rate (CGR) and relative growth rate (RGR). Decrease in applied water resulted in lower stomatal conductance (g_s) and photosynthesis rate (A_n). Ratio of photosynthesis rate to transpiration decreased when leaf vapor pressure deficit increased and in water and salinity stress conditions, transpiration efficiency of rapeseed decreased. Deficit irrigation had significant effect on slope of the fitted line to the relationship between A_n and g_s and VPD. In maximum water stress (0.35FI and 0.5 FI) relative to full irrigation, the reduction rate of A_n and g_s per each kPa increased VPD increased by 65.0 and 90.0%, respectively. There was no significant difference between the effects of salinity and planting methods on slopes of relationships between A_n and g_s and VPD. The rate of decrease in transpiration efficiency per each kPa increase in VPD was not affected by deficit irrigation and salinity and planting methods and its value was 0.610 g kg^{-1} $kPa^{-1}$and it is indicated that rapeseed was more tolerant to VPD variation in comparison with potato. So this index is a beneficial tool to compare crops and cultivars to VPD variations. As forage plant, rapeseed can be cultivated in soils with salinity of 3.4 dS m^{-1} and 11.7% deficit irrigation can be imposed without dry matter reduction and in-furrow planting method was proposed in salinity and water stress conditions in comparison with on-ridge planting.

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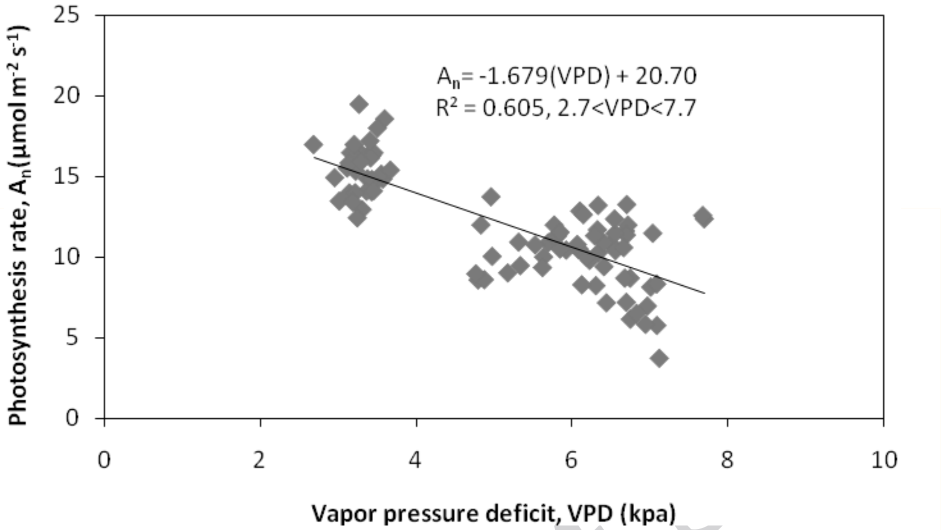

Figure 13. Relationship between photosynthesis rate (A_n) and vapor pressure deficit (VPD).

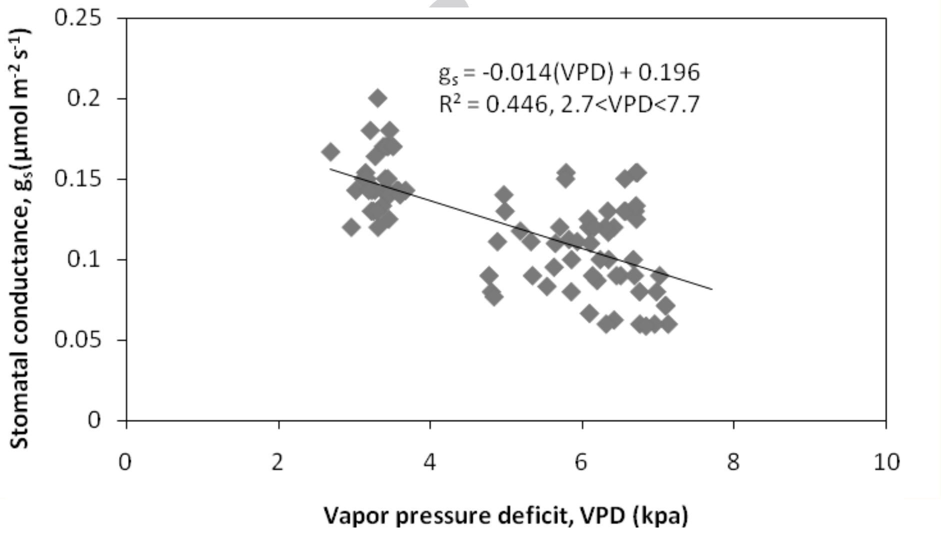

Figure 14. Relationship between stomatal conductance (g_s) and vapor pressure deficit (VPD).

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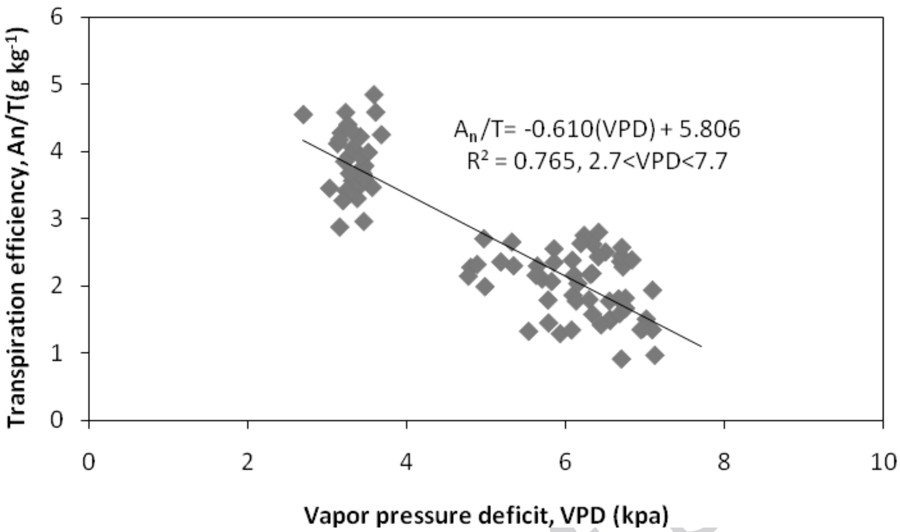

Figure 15. Relationship between Photosynthesis to transpiration ratio (A_n/T) and vapor pressure deficit (VPD).

Table 11. Relationship between photosynthesis rate (A_n in μmol m^{-2} s^{-1}), stomatal conductance (g_s in mol m^{-2} s^{-1}) and transpiration ratio (A_n/T) and vapor pressure deficit (VPD in kPa) in each irrigation, water salinity and planting methods treatment.

	A_n and VPD			g_s and VPD			A_n/T and VPD		
	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
Irrigation treatment									
FI**	-1.31^{a*}	20.28^{a}	0.58	-0.01^{a}	0.19^{a}	0.34	-0.55^{a}	5.92^{a}	0.57
0.65 and 0.75FI	-1.16^{a}	18.20^{b}	0.63	-0.003	0.14	0.04^{ss}	-0.76^{a}	6.68^{ab}	0.65
0.35 and 0.50FI	-2.16^{b}	21.85^{c}	0.73	-0.019^{b}	0.21^{b}	0.67	-0.55^{a}	5.35^{b}	0.73
Salinity levels, dS m^{-1}									
0.6	-1.49^{a}	21.10^{a}	0.50	-0.008^{a}	0.18^{a}	0.19^{s}	-0.51^{a}	5.47^{abc}	0.56
4.0	-1.94^{a}	22.47^{ab}	0.64	-0.014^{a}	0.20^{a}	0.35	-0.68^{a}	6.52^{a}	0.68
7.0 and 8.0	-1.94^{a}	21.63^{bc}	0.74	-0.018^{a}	0.21^{ab}	0.60	-0.59^{a}	5.60^{bc}	0.74
10.0 and 12.0	-1.255^{a}	17.35^{c}	0.46	-0.016^{a}	0.196^{b}	0.49	-0.57^{a}	5.47^{c}	0.76
Planting method									
On-ridge	-1.79^{a}	21.32^{a}	0.60	-0.014^{a}	0.198^{a}	0.41	-0.66^{a}	6.22^{a}	0.63
In-furrow	-1.44^{a}	20.28^{a}	0.44	-0.009^{a}	0.175^{a}	0.21	-0.45^{a}	5.17^{a}	0.55

** values followed by same letters in columns for each factor are not significantly different at 5% level of probability, ** FI: Full irrigation, SS, S: P_{value} of regression analysis are higher than 0.01 and 0.05, respectively.

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Acknowledgement

This research supported in part by a research project funded by Grant no. 91-GR-AGR 42 of Shiraz University Research Council, Drought National Research Institute, and the Center of Excellence for On-Farm Water Management. Furthermore, scholarship granted to the first author by Higher Education Ministry of I.R. of Iran is acknowledged.

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