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Growth and yield response of potato genotypes to deficit irrigation

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Abstract

In Ardabil region potato crop needs several irrigation, however ground water supplies are being exhausted due to reduced precipitation and intensive irrigation. In this research drought tolerance of 10 commercial potato cultivars was studied at three irrigation treatments (100%, 80% and 60% of required irrigation water) in Ardabil in a two years field study, 2013-2014. At harvest, marketable tuber yield, tuber weight per plant, mean tuber weight, tuber number per plant, percent tuber dry matter, plant height and the main stem diameter were measured. Also the stress indices such as water stress susceptibility (SSI), tolerance (TOL), mean productivity (MP), geometric mean productivity (GMP) and stress tolerance (STI) were determined and used to select the tolerant cultivars to water deficit. There were significant differences among irrigation treatments, cultivars and cultivars × irrigation treatments for all studied traits; between years and interaction of years × cultivars for marketable tuber yield, tuber weight per plant, mean tuber weight and tuber numbers per plant. The cultivar Satina produced the highest marketable tuber yield, tuber weight per plant, mean tuber weight and plant height and also had higher MP, GMP and STI indices in all three irrigation treatments, therefore, it can be recommended for cultivation under water deficit condition. Cultivar Caesar showed the lowest SSI and TOL indices under both mild and severe water deficit conditions, therefore it can be used in breeding programs for developing drought–tolerant potato cultivars. Under both mild and severe stress conditions a high correlation was found between marketable tuber yield and plant height, but a negative correlation existed between mean tuber weight and tuber number per plant. Cultivar Savalan showed the highest tuber dry matter content.

Keywords: Potato cultivars; Water deficit; Yield; Stress indices.

Introduction

Potatoes, *Solanum tuberosum* L., is the fourth most important food crop in the world after corn, rice and wheat, with an annual production of about 324 million tons (FAO, 2013). In Iran, annual potato crop acreage is about 144000 ha with mean yield of 27 t/ha and the total yield of about 4,000,000 tons (FAO, 2013). More than 20% of country's potato is produced in Ardabil province (Anonymous, 2013).

Water deficiency is the most important limiting factor of potato production throughout the world. The ever decreasing annual precipitation in the last decade has resulted in water shortage in the most potato growing regions of Iran, including Ardabil (Hassanpanah and Hassanabadi, 2010). During the last 30 years several potato cultivars have been introduced or released in Ardabil region, mostly on the basis of their higher yield and some other traits with no concern to their drought tolerance by Ardabil Agricultural and Natural Resources Research Station. Most of the growers have adapted to grow cultivars Agria and Draga mostly on the base of their higher yields. But in adapting these cultivars little or no attention has been paid to their drought tolerance (Hassanpanah, 2010). At the present, shortage of irrigation water and reduced precipitation is seriously threatening potato production in this region.

Since potato crop is sensitive to water deficit (Vayda, 1994; Foti et al., 1995; Rezai and Soltani, 1996; Shock et al., 2003; Shi et al., 2015), the provision of adequate amount of moisture in the soil is very essential to produce good crop. Moisture deficiency in the soil specially at the early growth stage delays germination and growth of the plants and results to reduced number of main stems per hill (Rezai and Soltani, 1996). The high sensitivity of potato to drought stress is mainly related to its shallow and poor root system (Harris, 1992; Allen et al., 1998; Onder, 2005) and its relatively lower water use efficiency (Iwama and Yamaguchi, 2006). Potato responds to water deficit with yield reduction and loss of tuber grade (Harris, 1992). Insufficient water supply in the period between emergence and beginning of tuber bulking results to reduced growth rate of foliage and reduced intercepted radiation (Tourneux et al., 2003). Even a brief period of water stress after tuber set can result in reduced tuber yield (Wright and Stark, 1990; Lynch et al., 1995; Rezai and Soltani, 1996 Baghani, 2009; Hassanpanah, 2010; Eskandari et al., 2011a; Eskandari et al., 2011b; Shi et al., 2015) and reduced quality (Ayas and Korukcu, 2010). Water deficiency reduces the amount of productive foliage (Jefferies and Mackerron, 1993a; Jefferies and Mackerron, 1993b; Tourneux et al., 2003), decreases canopy size (Tourneux et al., 2003; Schafleitner et al., 2007), reduces leaf number, leaf area index and plant height (Deblonde and Ladent, 2001; Sharma et al., 2015), shortens the vegetative growth period of potato (Deblonde and Ledent, 2001), decreases the rate of photosynthesis per unit of leaf area (Ta et al., 2003; Xu and Guang, 2006; Ferreira and Goncalves, 2007), reduces leaf water content (Shaw et al., 2002; Bürling et al., 2013; Shi et al., 2015) and lessens tuber number per hill, tuber size and marketable tuber yield of the potato crop (Allen and Scott, 1992; Gregory and Simmonds, 1992; Faberio et al., 2001; Yuan et al., 2003; Onder et al., 2005; Francois and De Proft, 2005; Ferreira and Concalves, 2007; Hassanpanah, 2010; Eskandari et al., 2011a; Alva et al., 2012; Cabello et al., 2012; Shi et al., 2015). Water deficiency also may decrease the tuber quality (Ta et al., 2003; Ayas and Korukcu, 2010). Hijman (2003) predicted that the worldwide yield production of potato will reduce 18% - 32% in the next 30 years (e.i. until 2033) due to water deficiency. Ferreira and Goncalves (2007) showed that in the hot and dry climate of Portugal irrigation level had clear effect on total tuber fresh weight with yields decreasing steadily from fully to 60% irrigation conditions. Alva et al. (2012) studied the effect of deficit irrigation in Northwest United States on potato yield and quality in three years with two cultivars of Ranger Russet and Umatilla Russet. They found that 14% to 17% deficit irrigation resulted in tuber yield reduction of 7% to 10% in both cultivars compared to full ET irrigation. Shi et al. (2015) found that in a mild water stress condition the yield of three different potato cultivars decreased from 37% to 64% compared to normal irrigation. Baghani

(2009), who investigated the effect of deficit irrigation on potato in Mashhad, concluded that under deficit irrigation conditions tuber yield of all potato cultivars studied were reduced significantly compared to the normal irrigation condition.

There are enough evidences indicating that potato cultivars differ in their tolerance to water stress (Martin and Miller, 1985; Miller and Martin, 1987a; Miller and Martin, 1987b; Harris, 1992; Jefferies and Mackerron, 1993a; Jefferies and Mackerron, 1993b; Iwama and Yamaguchi, 2006; Hassanpanah, 2010; Eskandari et al., 2011b; Cabello et al., 2012; Sharma et al., 2014; Shi et al., 2015). Identifying water deficit-tolerant potato cultivar (s) may be one approach to address the water shortage in potato producing areas. Some researchers have used stress tolerance indices to evaluate the response of different cultivars to water stress. Fischer and Maurer (1978) concluded that selection of genotypes based on stress susceptibility index (SSI) will select stress-tolerant genotypes, but with lower yield potential in some crops. Rosielle and Hamblin (1981) suggested tolerance (TOL) and mean productivity (MP) indices. They claimed that selections based on lower TOL index will result to selection of the genotypes in which the amount of yield reduction under stress conditions compared to normal conditions are low. Fernandez (1992) suggested geometric mean productivity (GMP) and stress tolerance (STI) indices. Hassanpanah (2010) used SSI, TOL, GM, GMP and STI indices to select drought–tolerant potato cultivar. Rabii et al. (2010) used GM, GMP and STI indices and Cabello et al. (2012) used TOL, GM, GMP, DTI (drought tolerance index) and DSI (drought susceptibility index) to select for water deficit-tolerant potato cultivars. Generally, deficit irrigation of potatoes may be difficult to manage, because even a brief period of water stress after tuber set can result in tuber yield (Shi et al., 2015) and quality reduction (Ayas and Korukcu, 2010). However, many researchers have shown that some potato cultivars are tolerant to moderate water deficit (Jefferies and Mackerron, 1987; Shock et al., 1998; Deblonde and Ledent, 2001; Shock and Feibert, 2001; Ierna and Mauromicale, 2006; Hassanpanah and Hoseinzadeh, 2007; Hassanpanah, 2010; Eskandari et al., 2011b; Shi et al., 2015). Therefore, the objectives of this study were to investigate the variation for drought tolerance in some commercial potato cultivars that have been introduced or released in the last 30 years to Ardabil province and to select high yielding potato cultivars under water deficit conditions.

Materials and Methods

Experiment location and potato cultivars

In this study 10 commercial potato cultivars (Table 1) were examined in Ardabil Agricultural and Natural Resources Research Station (latitude 38◦, 25' N; longitude 48◦, 30' and altitude 1390 m) at three irrigation treatments in a split plot experiment based on randomized complete block design with three replications in two years, 2013-2014.

Table 1. The origins, pedigree, introduced (or released) years and some characteristics of the potato cultivars investigated in this research.

Cultivars	Introduced year	Maturity	Tuber yield	Dry mater	Skin color	Plant high	Origen	Pedigree
Khavaran	2011	medium late	very high	high	yellow	tall	Iran	inbreeding of clone 397071-13 of CIP
Savalan	2009	medium late	very high	high	yellow	tall	Iran	2 91.612 × 88.05
Luca	2007	medium late	very high	medium	red	tall	Hungary	Not found
Satina	2004	medium late	high	medium	yellow	tall	Netherlands	Puntila × H 99/73
Sante	2002	medium late	medium	medium	yellow	short-medium	Netherlands	SVP Y 66-13-636 × SVP AM 66-42
Marfona	2000	medium late	medium	low	yellow	medium-tall	Netherlands	Primura × Konst 51-123
Caesar	1998	medium late	high	medium	light yellow	medium	Netherlands	Monalisa × Ropta b 1178
Agria	1994	medium late	high	high	yellow	tall	Germany	Quarta × Semlo
Aula	1988	late	medium	high	yellow	medium	Netherlands	H 6747/60 × CLIVIA
Draga	1981	early medium	medium	medium	light yellow	medium-tall	Netherlands	SVP 50-2017 × MPI19268

Irrigation treatments

Three irrigation treatments (irrigation with 100%, 80% and 60% of required water: e.i. normal irrigation, mild stress and severe stress conditions respectively) were considered as the main plots and 10 cultivars were considered as sub-plots. Each sub-plot consisted of six rows each six meters long; rows separated from each other by 75 cm and plants spaced 25 cm apart in the rows. Small earth bunds and a three meter distance between main-plots were provided to prevent water running from one main-plot to another. P, N and K fertilizers were applied based on the soil analysis result. The amount of water applied to each of the treatments during each irrigation event was equal to the amount of water lost as crop evapotranspiration (ET_c) between the two successive irrigation (I) dates minus the amount of effective precipitation (Re). A US Weather Bureau Class A pan (Epan) was used to determine the amount of daily evapotranspiration (Penman, 1948; Ahmadi Adle, 1996; Ferreira and Goncalves, 2007) and the amount of effective precipitation (Re) was obtained from a nearby weather station. Crop coefficients were obtained from FAO No. 56 publication's tables (Allen et al., 1998) and potential evapotranspiration (ET_0) was calculated using pan coefficient. The water content at field capacity (θFC), was measured by the method described by Tan (2005). Permanent wilting point was estimated by ROSETTA software (Shaap et al., 2001). Irrigation frequency (I), readily available water (RAW) and crop water requirement (ET_c) were calculated based on Allen et al. (1998):

$$I = RAW/ (ET_c - Re) \qquad \text{(Eq. 1)}$$

$$RAW = (\theta FC - \theta PWP)\ Y \times MAD \qquad \text{(Eq. 2)}$$

$$ET_c = ET_0 \text{-} K_c \qquad \text{(Eq. 3)}$$

RAW=Readily Available Water (mm); θFC=Field Capacity (mm); θPWP=Permanent Wilting Point (mm); Y=Root Depth (cm); MAD=Management Coefficient; ET_c=Crop Evapotranspiration (mm); ET_0=Potential Evapotranspiration (mm); K_c=Crop Coefficient. The amount of required water in each irrigation was delivered to each sub-plot by a polyethylene pipeline that was equipped to a water measuring gauge.

Yield components

During the growing season weeds, pests and diseases were controlled in a similar manner in all sub-plots. At the end of the growth season, when majority of plants were supposed to ripe, tubers from 7.5 m^2 of four middle rows from each sub-plot (ignoring the plants of 0.5 m at each end of the rows) were harvested to determine yield. Tubers were removed from the soil with a fork to recover all the tubers. In the laboratory, total tuber fresh weight, marketable tuber yield (tubers with size of 35 mm or more), tuber weight per plant, mean tuber weight, tuber number per plant, percent dry matter content of tubers, plant height and the main stem diameter were recorded.

Water stress susceptibility index (SSI), tolerance index (TOLI), mean productivity (MP), geometric mean productivity (GMP) and stress tolerance indices (STI) were calculated using the following equations:

$SSI = [1- (Y_s / Y_p)] / [1-(SI)],$ (Eq. 4)

Where $(SI)=1- (\grave{Y}_s / \grave{Y}_p)$ (Fischer and Maurer, 1978)

$TOL = Y_p - Y_s$ (Hossain et al., 1990) (Eq. 5)

$MP = (Y_p + Y_s)/ 2$ (Rosielle and Hamblin, 1981) (Eq. 6)

$GMP = \sqrt{(Y_s) \times (Y_p)}$ (Fernandez, 1992) (Eq. 7)

$STI = (Y_s \times Y_p) / \overline{Y}p$ (Fernandez, 1992) (Eq. 8)

In all of these equations, Y_s and Y_p are the yield of a given cultivar under water deficit and under full irrigation conditions, respectively; $\grave{Y}_s$ and $\grave{Y}_p$ being the mean yields of the 10 cultivars under water deficit and under full irrigation conditions, respectively.

Statistical analysis

The data were subjected to analysis of variance procedure for a split plot experiment based on a randomized complete block design with three replications using "SAS 9.1" (Steel and Torrie, 1980). The comparison of treatment means were carried out using Duncan's multiple range test. Correlation analysis between tuber yield and other traits were computed using SPSS ver.16. To determine the most effective index on tuber yield under mild and severe water stress conditions the stepwise regression method was use (Durbin and Watson, 1951). Regression analysis between tuber yield and tolerance indices were calculated using SPSS ver. 16.

Results

The ANOVA demonstrated that there were significant differences between irrigation treatments and interaction between cultivar × irrigation treatments for all studied traits (except for percent tuber dry matter). There were highly significant differences among cultivars for all studied traits. Meanwhile, there were significant differences between years and year × cultivar for marketable tuber yield, tuber weight per plant, mean tuber weight and tuber numbers per plant; year × irrigation treatments for marketable tuber yield, mean tuber weight and tuber numbers per plant. Year × irrigation treatments × cultivar was significant only for the tuber number per plant (Table 2).

Deficit irrigation resulted in significant reduction of marketable tuber yield, tuber weight per plant, mean tuber weight, tuber number per plant, plant height and main stem diameter (Table 3). Cultivars Khavaran, Savalan, Luca, Satina and Aula had the highest marketable tuber yields in normal irrigation; cultivars Khavaran, Savalan, Luca, Satina, Agria and Aula under mild stress and cultivars Satina and Khavaran under severe stress (Table 3). Cultivars Caesar, Satina and Khavaran had the highest tuber weight per plant in normal irrigation; cultivars Satina and Caesar under mild stress and cultivar Satina under severe stress. The highest mean tuber weight in normal irrigation were observed in cultivars Satina, Draga, Caesar, Marfona and Sante; under mild stress in cultivars Caesar, Satina, Marfona, Luca and; under severe stress in cultivars Satina, Caesar, Savalan and Aula. The highest tuber number per plant in normal irrigation were observed in cultivars Savalan and Aula and cultivar Savalan produced the highest number of tuber per plant under both mild and severe stress conditions. The highest plant height in normal irrigation was observed in cultivars Satina, Caesar and Draga; under mild stress conditions in cultivars Caesar and Satina and under severe stress conditions in Satina and Caesar; and Luca. The highest main stem diameter in normal irrigation was observed in cultivars Luca, Savalan and Khavaran; under mild stress in cultivars Savalan, Khavaran and Satina and under severe stress in cultivars Khavaran, Satina and Caesar. Under severe stress condition, cultivar Satina showed the highest marketable tuber yield, tuber weight per plant, mean tuber weight and plant height. Cultivar Caesar showed the mean tuber weight equal to Satina and the lowest number of tuber per plant under both mild and severe stress conditions (Table 3).

After running a simple analysis of variance between the studied years, error homogeneity test (Bartlett, 1937) conducted. Since the experimental error was homogenous, combined analysis of variance was conducted and F-test was carried out on the basis of the expected mean squares. Since there were significant differences between the cultivars, irrigation treatments and irrigation × cultivar interaction, therefore mean squares of the significant interaction effects were sliced specially for the irrigation × cultivar interaction (Table 3). There were significant difference between each level of irrigation treatments in terms of marketable tuber yield, tuber weight per plant, mean tuber weight, plant hight and main stem diameter. But in terms of tuber number per plant significant difference observed only between mild and severe stress conditions (Table 2).

In irrigation with 100% of required water with respect to marketable tuber yields, cultivars Khavaran, Savalan, Luca, Satina, Sante, Marfona, Caesar, Agria and Aula; with respect to tuber weight per plant, cultivars Khavaran, Luca, Satina, Caesar and Draga; with respect to mean tuber weight, cultivars Khavaran, Luca, Satina, Sante, Marfona, Caesar, Agria, Aula and Draga; with respect to tuber number per plant, cultivars Savalan and Aula; with respect to plant height, cultivars Caesar, Satina and Luca; and with respect to main stem diameter, cultivars Savalan, Khavaran and Luca were in the same group and no significant differences were observed among the cultivars in each group (Table 4).

In irrigation with 80% of required water with respect to marketable tuber yield, cultivars Khavaran, Savalan, Luca, Satina, Sante, Marfona, Caesar , Agria and Aula, with respect to tuber weight per plant, cultivars Khavaran, Savalan, Luca, Satina, Sante, Marfona, Caesar, Aula and Draga; with respect to mean tuber weight, cultivars Luca, Marfona and Caesar; with respect to tuber number per plant, cultivars Savalan and Aula; with respect to plant height, cultivars Caesar, Satina and Luca and with respect to main stem diameter, cultivars Khavaran, Savalan, Satina, Luca, Caesar and Aula were in the same group and no significant differences were observed among the cultivars in each group (Table 4).

In irrigation with 60% of required water with respect to marketable tuber yield, cultivars Satina, Khavaran, Caesar, Luca, Savalan, Sante and Aula; with respect to tuber weight per plant, cultivars Satina and Savalan; with respect to mean tuber weight, cultivars Satina, Caesar, Marfona, Khavaran, Savalan, Luca, Sante and Aula; with respect to tuber number per plant, cultivars Savalan, Agria, Luca, Khavaran, Satina, Aula and Draga; with respect to plant height, cultivar Satina and with respect to main stem diameter, cultivars Khavaran, Satina, Caesar, Savalan and Luca were in the same group and no significant differences were observed among the cultivars in each group (Table 4).

Table 2. Analysis of variance of the studied traits in potato cultivars under three different irrigation treatments during two years.

Source of Variation	D.F.	Marketable tuber yield	Tuber weight per plant	Mean tuber weight	Tuber number per plant	Plant height	Main stem diameter	Dry matter percent
Year (Y)	1	4919**	19753968**	110057**	371.69**	0.061	0.067	0.242
Error 1	4	89.06	51052	789	14.01	117	0.16	0.70
Irrigation treatment (I)	2	1093**	696804**	3579**	194.96**	12237**	25.84**	0.949
Y × I	2	79.86*	6372.58	3966**	8.72**	137	0.59	0.009
Error 2	8	3.28	2591	219.20	0.38	156	2.088	0.70
Cultivars (C)	9	111**	104701**	2131.27**	18.12**	4773**	5.98**	44.94**
I × C	18	114**	21879*	5560.28**	3.35**	1283**	1.176**	0.16
Y × C	9	172**	189787**	2203.00**	12.34**	92.74	0.63	0.93
Y × I × C	18	16.32	19424	577.60	3.52**	48.23	0.481	0.41
Error 2	108	26.41	13551	539.32	1.708	87.67	0.41	0.70
C.V.%		18.07	14.63	23.64	16.05	7.69	14.23	4.01
The slicing for effects of irrigation*cultivar interaction - mean squares								
normal irrigation	9	63.55**	32782**	11.04**	652.78^{ns}	865.32**	3.52**	-
mild stress	9	42.48*	28262**	5.94**	1387.01**	2361.78**	2.11**	-
severe stress	9	55.51*	97417**	7.85**	1212.06*	4112.29**	2.69**	-

* and ** significant at P≤0.05 and ≤0.01 probability level, respectively.

Table 3. Mean comparisons of marketable tuber yield, tuber weight per plant, mean tuber weight, tuber number per plant, plant height and main stem diameter in 10 potato cultivars under three different irrigation treatments during two years, 2013-2014.

Irrigation treatments	Cultivars	Marketable tuber yield (ton ha-1)		Tuber weight per plant (g)		Mean tuber weight (g)		Tuber number per plant		Plant height (cm)		Main stem diameter (mm)	
Irrigation with 100% of required water (normal irrigation)	Khavaran	37.0	a*	951	abc	87.5	c-f	10.6	bc	103	ijk	5.83	abc
	Savalan	36.3	ab	901	a-f	71.4	f	12.7	a	94.0	jkl	6.11	ab
	Luca	33.8	a-d	921	a-d	83.5	c-f	10.9	bc	92.0	kl	6.33	a
	Satina	33.8	a-d	983	ab	100	b-f	9.33	c-f	130	def	5.50	bcd
	Sante	32.1	a-e	917	a-e	91.3	b-f	9.92	bcd	109	hi	4.00	fgh
	Marfona	31.8	a-f	814	c-h	97.5	b-f	8.40	d-g	102	ijk	5.50	bcd
	Caesar	27.4	c-i	1053	a	99.3	b-f	10.4	bc	117	gh	4.50	e-g
	Agria	31.5	a-f	864	b-g	87.0	c-f	9.61	cde	105	ij	4.50	e-g
	Aula	34.6	abc	858	b-g	74.9	ef	11.3	ab	93.0	jkl	4.78	d-g
	Draga	27.5	c-i	824	b-g	100	b-f	8.25	f-i	109	hi	5.17	cde
Irrigation with 80% of required water (mild stress)	Khavaran	31.2	b-h	799	c-i	102	b-f	7.50	g-j	121	fg	4.83	def
	Savalan	29.8	b-h	782	d-i	78.9	e-f	9.92	bcd	105	ij	5.17	cde
	Luca	29.4	b-h	795	g-j	116	abc	6.76	g-j	147	bc	4.50	efg
	Satina	29.6	b-h	863	b-g	104	b-e	7.42	g-j	150	bc	4.67	d-g
	Sante	28.7	c-h	762	d-i	103	b-f	7.19	g-j	127	efg	3.17	ij
	Marfona	26.2	e-i	755	e-i	112	a-d	6.47	hij	134	de	3.56	hij
	Caesar	27.3	d-i	849	b-g	132	a	6.89	g-j	153	b	4.67	d-g
	Agria	29.2	b-h	672	hij	86.7	c-f	7.57	g-j	103	ijk	4.33	e-h
	Aula	29.5	b-h	810	c-h	94.5	b-f	8.50	d-g	122	efg	4.50	efg
	Draga	24.7	f-j	737	ghi	94.9	b-f	7.75	c	100	ijk	4.33	e-h
Irrigation with 60% of required water (severe stress)	Khavaran	27.4	c-i	746	f-i	99.4	b-f	7.06	g-j	131	def	4.67	d-g
	Savalan	24.5	f-j	821	c-h	102	b-f	8.08	e-h	148	bc	4.33	e-h
	Luca	26.1	e-i	721	g-j	98.0	b-f	7.35	g-j	131	def	4.33	e-h
	Satina	28.9	c-h	908	a-f	122	ab	6.81	g-j	180	a	4.58	efg
	Sante	23.6	hij	642	ij	99.5	b-f	6.17	ij	120	fgh	3.06	j
	Marfona	21.0	g-i	448	k	115	abc	3.97	hij	140	cd	3.17	ij
	Caesar	24.1	ij	729	ghi	122	ab	5.83	g-j	155	b	4.50	efg
	Agria	20.9	f-j	575	jk	83.6	c-f	7.39	g-j	87	ijk	3.89	ghi
	Aula	24.8	f-j	702	g-j	102	b-f	6.81	g-j	129	d-g	2.89	j
	Draga	19.1	j	650	ij	81.5	def	7.26	g-j	103	ijk	3.89	ghi

* Means followed with the same letters in each column are not significantly different at 0.05% probability level using Duncan's multiple range test.

Table 4. Mean comparisons of marketable tuber yield, tuber weight per plant, mean tuber weight, tuber number per plant, plant height and main stem diameter in 10 potato cultivars for each level of the irrigation treatment, during two years, 2013-2014.

Irrigation treatments	Cultivars	Marketable tuber yield (ton ha-1)		Tuber weight per plant (g)		Mean tuber weight (g)		Tuber number per plant		Plant height (cm)		Main stem diameter (mm)	
Irrigation with 100% of required water (normal irrigation)	Khavaran	37.0	a*	951	abc	87.5	ab	10.6	bcd	103	cde	5.83	abc
	Savalan	36.3	a	901	bcd	71.4	b	12.7	a	94	de	6.11	ab
	Luca	33.8	a	921	abcd	83.5	ab	10.9	bc	92	e	6.33	a
	Satina	33.8	ab	983	ab	100	a	9.33	de	130	a	5.50	bcd
	Sante	32.1	ab	917	bcd	91.3	ab	9.92	bcd	109	bc	4.00	f
	Marfona	31.8	ab	814	d	97.5	ab	8.40	e	102	cde	5.50	bcd
	Caesar	27.4	b	1053	a	99.3	a	10.4	bcd	117	b	4.50	ef
	Agria	31.5	ab	864	bcd	87.0	ab	9.61	cde	105	cd	4.50	ef
	Aula	34.6	a	858	bcd	74.9	ab	11.3	ab	93	e	4.78	de
	Draga	27.5	b	824	cd	100	a	8.25	e	109	bc	5.17	cde
Irrigation with 80% of required water (mild stress)	Khavaran	31.2	a	799	ab	102	bcd	7.50	bc	121	c	4.83	ab
	Savalan	29.8	ab	782	ab	78.9	d	9.92	a	105	d	5.17	a
	Luca	29.4	ab	795	ab	116	ab	6.76	c	147	a	4.50	ab
	Satina	29.6	ab	863	a	104	bcd	7.42	bc	150	a	4.67	ab
	Sante	28.7	ab	762	ab	103	bcd	7.19	bc	127	bc	3.17	c
	Marfona	26.2	ab	755	ab	112	abc	6.47	c	134	b	3.56	c
	Caesar	27.3	ab	849	a	132	a	6.89	c	153	a	4.67	ab
	Agria	29.2	ab	672	b	86.7	cd	7.57	bc	103	d	4.33	b
	Aula	29.5	ab	810	a	94.5	bcd	8.50	ab	122	c	4.50	ab
	Draga	24.7	b	737	ab	94.9	bcd	7.75	bc	100	d	4.33	b
Irrigation with 60% of required water (severe stress)	Khavaran	27.4	a	746	bc	99.4	ab	7.06	abc	131	de	4.67	a
	Savalan	24.5	abc	821	ab	102	ab	8.08	a	148	bc	4.33	ab
	Luca	26.1	ab	721	bc	98.0	ab	7.35	ab	131	de	4.33	ab
	Satina	28.9	a	908	a	122	a	6.81	abc	180	a	4.58	ab
	Sante	23.6	abc	642	cd	99.5	ab	6.17	bc	120	e	3.06	d
	Marfona	21.0	bc	448	e	115	a	3.97	d	140	cd	3.17	cd
	Caesar	24.1	abc	729	bc	122	a	5.83	c	155	b	4.50	ab
	Agria	20.9	bc	575	de	83.6	b	7.39	ab	87	g	3.89	bc
	Aula	24.8	abc	702	bcd	102	ab	6.81	abc	129	de	2.89	d
	Draga	19.1	c	650	cd	81.5	b	7.26	abc	103	f	3.89	bc

* Means with the same letters in each column are not significantly different at 0.05% probability level using Duncan's multiple range test.

Irrigation treatments effect on the percent tuber dry matter was not significant, however there were significant differences among the cultivars in this respect and cultivars Savalan and Draga with 23.66% and 18.0% tuber dry matter produced the highest and lowest percent tuber dry matter respectively (Table 5).

Table 5. Mean comparisons of percent tuber dry matter in 10 potato cultivars in two years.

Cultivars	Khavaran	Savalan	Luca	Satina	Sante	Marfona	Caesar	Agria	Aula	Draga
Mean	22.10^{b}	23.66^{a}	21.66^{bc}	20.50^{fe}	21.16^{cd}	19.00^{g}	20.25^{f}	21.3^{cd}	21.0^{df}	18.0^{h}

Correlation analysis revealed that under normal irrigation condition there was a negative significant correlation (r= -0.69*) between mean tuber weight and tuber weight per plant (Table 6), which indicates that with higher tuber weight per plant there was a significant decrease in the mean tuber weight. Also under the normal irrigation condition a highly negative significant correlation (r= -0.85**) was observed between tuber number per plant and mean tuber weight, which demonstrates that the increased tuber number results to a decrease in mean tuber weight. In contrast, highly positive significant correlations were observed between plant height - mean tuber weight (r=0.79**) and between tuber number per plant - tuber weight per plant (r=0.61*) under normal irrigation condition. Under mild stress condition, there were highly significant correlations between marketable tuber yield and plant height (r=0.74**) and mean tuber weight and plant height (r=0.85**) (Table 7). However, the correlation between mean tuber weight and tuber number per plant was negatively significant (r= -0.78**). Under severe stress condition, highly significant correlations were found between marketable tuber yield-tuber weight per plant (r=0.77**) and mean tuber weight-plant height (r=0.91) (Table 8). Also there were significant correlations between marketable tuber yield-plant height (r=0.62*); marketable tuber yield-main stem diameter (r=0.64*) and tuber weight per plant-plant height (r=0.70*). However there was a negative correlation between mean tuber weight and tuber number per plant (r=0.54).

Table 6. Correlation between different traits in potato cultivars in irrigation with 100% of required water (normal irrigation).

Traits	Marketable tuber yield	Tuber weight per plant	Mean tuber weight	Tuber number per plant	Plant height	Main stem diameter
Marketable tuber yield	-					
Tuber weight per plant	-0.01	-				
Mean tuber weight	0.20	-0.69*	-			
Tuber number per plant	0.31	0.61*	-0.85**	-		
Plant height	0.49	-0.42	0.79**	-0.53	-	
Main stem diameter	-0.06	0.54	-0.28	0.29	-0.34	-

* and ** significant at P≤0.05 and ≤0.01, respectively.

Table 7. Correlation between different traits in potato cultivars in irrigation with 80% of required water (mild stress).

Traits	Marketable tuber yield	Tuber weight per plant	Mean tuber weight	Tuber number per plant	Plant height	Main stem diameter
Marketable tuber yield	-					
Tuber weight per plant	0.25	-				
Mean tuber weight	0.51	-0.24	-			
Tuber number per plant	-0.03	0.31	-0.78**	-		
Plant height	0.74**	0.09	0.85**	-0.60*	-	
Main stem diameter	0.37	0.41	-0.22	0.56	-0.07	-

* and ** significant at P≤0.05 and ≤0.01, respectively.

Table 8. Correlation between different traits in potato cultivars in irrigation with 60% of required water (severe stress).

Traits	Marketable tuber yield	Tuber weight per plant	Mean tuber weight	Tuber number per plant	Plant height	Main stem diameter
Marketable tuber yield	-					
Tuber weight per plant	0.77**	-				
Mean tuber weight	0.29	0.53	-			
Tuber number per plant	0.61*	0.23	-0.54	-		
Plant height	0.62*	0.70*	0.91**	-0.21	-	
Main stem diameter	0.64*	0.49	0.18	0.44	0.38	-

* and ** significant at P≤0.05 and ≤0.01, respectively.

The correlation analysis between tuber yield under normal irrigation (YN) and mild water stress conditions (YM) and stress indices revealed that there were highly significant correlations between tuber yield and MP, GMP and STI indices (Table 9). To determine the most effective index on tuber yield under mild water stress condition the stepwise regression method was used. The value of Durbin-Watson statistic was 2.281 (Table 10). The regression analysis revealed that the SSI and STI indices are very effective and important indices for selection of potato cultivars with higher tuber yield under mild water stress condition. In the fitted model the value of R^2 was 0.99 which indicates that under mild water stress condition 99% of tuber yield variation is predicable by SSI and STI indices.

The correlation analysis between tuber yield and stress indices under normal irrigation and severe water deficit conditions revealed that there were significant correlations between tuber yield and all stress indices at 5% and 1% levels of probability (Table 11). Under severe water deficit condition the correlation between tuber yield and MP, GMP and STI indices were highly significant. Also there were significant correlations between STI and each one of other stress indices. Therefore, it can be concluded that MP, GMP and STI indices can be effectively used to select cultivars under normal irrigation and under mild and severe water stress conditions. The value of Durbin-Watson statistic was 2.25 for this experiment. The results of regression analysis revealed that STI and SSI indices are the most effective and important indices for selection of higher yielding cultivars under severe water stress condition (Table 12).

Table 9. Correlation analysis between tuber yield under normal irrigation (YN) and mild water deficit condition (YM) with water deficit stress indices and drought tolerance indices.

Traits	SSI	TOL	MP	GMP	STI	YN	YM
SSI	-						
TOL	0.94**	-					
MP	-0.22	0.08	-				
GMP	-0.27	0.03	0.99**	-			
STI	-0.27	0.02	0.99**	0.99**	-		
YN	0.20	0.49	0.91**	0.89**	0.88**	-	
YM	-0.62*	-0.36	0.90**	0.92**	0.92**	0.643*	-

* and ** significant at P≤0.05 and ≤0.01 respectively.

Table 10. Regression analysis of variance between tuber yield under mild water deficit condition with water deficit stress indices and drought tolerance indices.

Source	DF	SS	MS	F	P
Regression	2	33.636	16.818	4166	0.000
Residual Error	7	0.028	0.004		
Total	9	33.664			

R-Sq=99% R-Sq (adj)=99%; Durbin-Watson statistic=2.281.

Table 11. Correlation analysis between tuber yield under normal irrigation (YN) and severe water deficit condition (SY) with water deficit stress indices and drought tolerance indices.

Traits	SSI	TOL	MP	GMP	STI	YN	YS
SSI	-						
TOL	0.98**	-					
MP	0.60*	0.71*	-				
GMP	0.58	0.69	0.99**	-			
STI	0.59*	0.70*	0.99**	0.99**	-		
YN	0.75*	0.84**	0.97**	0.97**	0.97**	-	
YS	0.29	0.42	0.93**	0.94**	0.93**	0.84**	-

* and ** significant at P≤0.05 and ≤0.01, respectively.

Table 12. Regression analysis of variance between tuber yield under severe water deficit condition with water deficit stress indices and drought tolerance indices.

Source	DF	SS	MS	F	P
Regression	2	33.636	16.818	4166	0.000
Residual Error	7	0.028	0.004		
Total	9	33.664			

R-Sq=99% R-Sq (adj)=99%; Durbin-Watson statistic=2.281.

Based on the calculated stress index (SI) the mean percent losses of marketable tuber yield were 12% and 27% for mild and severe water stress conditions, respectively. The Caesar cultivar demonstrated the highest amount of tolerance to both mild and severe water deficit conditions, since it had the lowest SSI and TOL indices (Table 13). Cultivars Khavaran, Savalan, Satina and Luca showed the highest MP, GMP and STI indices under both normal and water deficit conditions, but their SSI and TOL indices also were relatively high.

Table 13. Mean tolerance and sensitivity indices of 10 potato cultivars under mild and severe water stress conditions during two years, 2013-2014.

Cultivars	SSI		TOL		MP		GMP		STI	
	Mild	Severe	Mild	Severe	Mild	Severe	Mild	Severe	Mild	Severe
Khavaran	1.30	0.95	5.83	9.61	34.1	32.2	34.0	31.9	1.06	0.94
Savalan	1.49	1.19	6.55	11.8	33.1	30.4	32.9	29.8	1.00	0.82
Luca	1.07	0.84	4.38	7.71	31.6	30.0	31.5	29.7	0.92	0.81
Satina	1.01	0.53	4.14	4.91	31.7	31.3	31.7	31.2	0.92	0.90
Sante	0.85	0.97	3.32	8.46	30.4	27.8	30.3	27.5	0.85	0.70
Marfona	1.45	1.24	5.59	10.7	29.0	26.4	28.8	25.9	0.77	0.62
Caesar	0.03	0.44	0.10	3.30	27.3	25.8	27.3	25.7	0.69	0.61
Agria	0.60	1.24	2.30	10.6	30.4	26.2	30.4	25.7	0.85	0.61
Aula	1.22	1.04	5.13	9.79	32.0	29.7	31.9	29.3	0.94	0.79
Draga	0.84	1.12	2.80	8.39	26.1	23.3	26.1	23.0	0.63	0.49

Cultivar Satina produced the highest mean tuber weight and the highest plant height under normal irrigation; higher marketable tuber yield and main stem diameter under mild stress conditions; highest marketable tuber yield, highest tuber weight per plant, highest mean tuber weight and highest plant height under severe water deficit conditions. Satina also had relatively better drought tolerance indices. Also cultivars Khavaran and Savalan, that have been bred and released in recent years in Ardabil, performed relatively better than some other cultivars in terms of marketable tuber yield under normal irrigation and mild stress conditions and with respect to MP, GMP and STI indices under mild and severe stress conditions (Table 13). Cultivar Caesar showed the lowest SSI and TOL indices under both mild and severe stress conditions which is an indication of being drought-tolerant.

Discussion

Deficit irrigation reduced all the growth traits of potato cultivars, except the percent tuber dry matter. The marketable tuber yield is the most important trait for the growers. The highest marketable tuber yield was observed on cultivar Khavaran in all three irrigation treatments (37, 31.2 and 27.4 ton/ha), while the lowest values were obtained in cultivar Draga (27.5, 24.7 and 19.1 ton/ha respectively). Among 10 potato cultivars studied in this research, cultivar Satina ranked the first and the second with respect to tuber weight per plant and marketable tuber yield (29.6 ton/ha) under mild stress condition; but it produced the highest marketable tuber yield, the highest tuber weight per plant and the highest mean tuber weight under severe stress condition.

There is a widespread acceptance of the notion that some potato cultivars are more of drought-tolerant than the others (Vos, 1986; Jefferies and Mackerron, 1987; Lynch and Tai, 1989; Harris, 1992; Gregory and Simmonds, 1992; Iwama and Yamaguchi, 2006). Jefferies and Mackerron (1987) in about 30 years ago showed that potato cultivars Pentland Crown, Pentland Dell and Desiree were drought-tolerant, whereas cultivars

Maris Piper and Record were drought-susceptible. Deblonde and Ledent (2001) studied drought tolerance of six potato cultivars by subjecting them to three levels of water stress in Belgium and found that the cultivars were different in their response to water stress. Our results also revealed that potato cultivars responded differently to water deficit and are in compliance with the results of the above mentioned researches. Shock and Feibert (2001) found that at Oregon State University Experiment Station, USA, potato cultivars responded differently to deficit irrigation and concluded that in eastern Oregon the adoptions of new drought-tolerant potato cultivars by breeders can make it desirable to re-examine deficit irrigation in potato crop. Ierna and Mauromicale (2006) investigated the growth response of two potato cultivars Sieglinde and Spunta to moderate water deficit in Catania, Italy and concluded that Sieglinde was more tolerant than Spunta. In another research Shock et al. (2007) concluded that clever management of potato irrigation by using drought-tolerant potato cultivars can return greater profits to potato growers while enhancing the sustainability of production by avoiding environmental degradation. Shi et al. (2015) evaluated the effect of long-term drought stress on some potato cultivars under the field conditions in China and concluded that drought-tolerant cultivars (Kexin no.1 and Konyu no.3) produced higher tuber yields under drought conditions due to an increased number of tubers per hill and increased individual tuber weight compared with the drought-sensitive cultivar (Neishu no.7). Our findings are similar to the results obtained by these scientists.

Our results demonstrated that deficit irrigation significantly reduced the marketable tuber yield in most of the cultivars included in this research (Table 3), nevertheless, cultivar Satina clearly performed the best under both water deficit treatments. Hassanpanah and Hassanabadi (2010) also evaluated the response of six potato genotypes to deficit irrigation in three irrigation regimes in Ardabil and found that Savalan cultivar (which has been released since 2012) and clones 397008-10 and 397009-3 were more drought tolerant, while Agria (the most widely planted cultivar in Ardabil) was the most susceptible cultivar to water deficit. We also showed that Agria is a drought-sensitive cultivar, but cultivar Savalan was not as tolerant as Satina and Caesar cultivars in our studies. Eskandari et al. (2011a) who also studied the effects of three irrigation regimes on yield of three potato cultivars (Agria, Almera and Sinura) in Mashhad found that deficit irrigation significantly reduced the tuber yield of all three cultivars and in all irrigation regimes there were significant differences among tuber yields of the cultivars. Deficit irrigation resulted in more yield reduction in cultivars Almera and Sinura compared to Agria. Cultivar Agria produced highest tuber yield and highest number of marketable tuber under water deficit condition. Conversely, in our studies (and also in Hassanabadi's (2010) results) Agria cultivar that has been introduced to Ardabil in 1994 was a drought-sensitive cultivar which is in contradiction with the results of the above stated research. This inconsistency may be related to the smaller number of cultivars that were examined by Eskandari et al. (2011a) and Eskandari et al. (2011b).

In our studies deficit irrigation had no significant effect percent tuber dry matter, however cultivars Savalan and Khavaran ranked first and second in this respect among the studied cultivars. Eskandari et al. (2011a) concluded that deficit irrigation had no significant effects on percent tuber dry matter but there were significant differences among studied cultivars (Agria, Sinura and Almera) in this respect and cultivar Almera produced the highest percent tuber dry matter under normal irrigation. However Ayas and Korukcu (2010) found that there were a negative linear relationship between percent tuber dry matter with the amount of irrigation water. But Sharma et al. (2014) indicated that in Jodhpur, India conditions deficit irrigation did not influence percent tuber dry matter. The results of our studies are in consistence with the findings of these scientists. Percent tuber dry matter is an important quality attributes of potato tubers specially for processing use, higher percent dry mater results to higher processing efficiency, more homogeneity of chips and French fries and reduced oil consumption and higher benefit to the growers and industry.

Satina cultivar also showed the highest tolerance to water deficit stress in terms of GMP, MP and STI indices and could be labeled as drought tolerant cultivar. Cultivar Caesar showed the lowest SSI and TOL indices under both mild and severe water deficit conditions which is an indication of having drought tolerance capability and could be used in breeding programs for developing drought-tolerant potato cultivars. Cultivar Savalan showed the highest percent tuber dry matter. Hassanpanah and Hoseinzadeh (2007), who examined some potato cultivars tolerance to water deficit in Ardabil by using the GMP, MP, STI, SSI and TOL indices, concluded that cultivar Caesar was tolerant to water deficit condition. Also in our studies, cultivar Caesar showed the lowest SSI and TOL indices under both mild and severe water deficit conditions which is an indication of having drought tolerance potential. Rabii et al. (2010) in their studies on stress indices of potato cultivars concluded that MP, GMP and TOL were the most effective indices for identifying drought-tolerant potato cultivars. Also stress indices of SSI, MP, GMP, STI and MSTI were used by Hassanpanah (2010) under *in-vivo* and *in-vitro* conditions to identify drought-tolerant cultivars in Ardabil and cultivar Caesar was identified as drought-tolerant cultivar on the basis of lower stress susceptibility (SSI) (0.68 and 0.47) and lower TOL indices (1.67 and 1.67) under mild and severe water stress conditions respectively. Cabello et al. (2012) calculated stress indices of MP, GMP, TOL, DTS (drought tolerance index) DSI (drought susceptibility index) and YSI (yield stability index) from tuber yield under drought and irrigated conditions to compare yield based drought tolerance in a large set of potato accessions from CIP world potato collections which included improved potato cultivars, genetic stocks and landraces of potato. They concluded that three indices of MP, GMP and DTI were the most effective indices for identifying genotypes combining high yield potential with high yield under drought condition. In our studies cultivar Caesar was selected as drought-tolerant based on its lower SSI (0.03 and 0.440) and lower TOL (0.10 and 3.30) indices under mild and severe water stress conditions respectively among 10 potato cultivars evaluated in this study. Cultivars Savalan and Khavaran also were selected on the basis of MP, GMP and STI indices.

The differential responses of the potato cultivars to water deficit suggest a strategy for the improvement of tolerance to moderate drought. However, in any potato production region, the availability of drought-tolerant cultivars, the cost and availability of irrigation water, the market price of potatoes and the analysis of cost-benefit will determine whether the practice of deficit irrigation is profitable or not. During the last 30 years several potato cultivars have been introduced or released in Ardabil region, from which cultivars Draga (introduced in 1981) and Agria (introduced in 1994) have been adapted by the growers mostly on the basis of their higher yields and yellow flesh color and currently Agria is the most widely cultivated potato cultivar in Ardabil region. However, both cultivars proved to be relatively sensitive to deficit irrigation in our studies. We could not find any chronological relation between years of introduction or release and water deficit-tolerance of the studied cultivars, probably because in evaluation of potato cultivars drought tolerance has not been the main concern of the researchers and has been neglected. Giving the ever increasing water shortage and increased cost of the irrigation water we recommend the water deficit-tolerant cultivar Satina (which has been introduced in 2004) as an alternative to Agria and Draga cultivars for situations where the cost of water is high or the availability of irrigation water is limited. Cultivar Caesar (introduced in 1998), that showed the lowest SSI and TOL indices under both mild and severe water deficit conditions might have drought tolerance potentials and it should be used in breeding programs for developing drought-tolerant potato cultivars. In situations where the percent dry matter and tuber quality is of prime importance, cultivars Savalan and Khavaran should be grown if enough irrigation water is available. These two cultivars have also yellow skin and yellow flesh color which are preferred by the consumers.

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