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RESEARCH ARTICLE

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Supplemental irrigation management of rainfed grapevines under drought conditions using the CropSyst model

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Abstract

Aim of study: To determine how much water should be used and when it should be applied in rain-fed grapevine using a cropping system simulation model (CropSyst), and also the economic analysis of supplemental irrigation for rainfed grapevine.

Area of study: This study was conducted at the School of Agriculture, Shiraz University, Shiraz, Iran, in 2012, 2013 and 2014.

Material and methods: The CropSyst model was calibrated to predict the rainfed yields of 'Askari' and 'Yaghooti' grapevines in different climates using four amounts of SI: 250 L (I1), 500 L (I2), 1000 L (I3) and 0 (I4), five SI times: single in March (T1), single in April (T2), single in March + single in April (T3), single in May (T4) and single in June (T5).

Main results: Treatment T3 increased the average simulated yield of 'Askari' by 15% to 40% at regions with P/ETo>0.6, 17% to 61% at $0.2<P/ET_O<0.6$, and 26% to 61% at $P/ET_O<0.2$, while in 'Yaghooti' it increased about 2% to 41% at regions with P/ETo>0.6, 4% to 36% at $0.2<P/ET_O<0.6$ and 2% to 26% at $P/ET_O<0.2$. By increasing the water price by 30% and 50%, net benefits for the 'Askari' decreased by about 31% and 54%, while 6% and 18%, for 'Yaghooti' respectively.

Research highlights: The CropSyst model can successfully predict soil water content and grapevine yields. Application of SI in May increased significantly the grapevine yield as compared to other SI times.

Additional keywords: simulated yield; finance analysis; land limiting conditions; optimum irrigation water; precipitation; semi-arid climate

Abbreviations used: AI (aridity index); *CA* (annual uniform production cost); C(I) (annual production costs per unit of land); d (Wilmot index of agreement); EC (electrical conductivity); ETo (reference evapotranspiration); FC (field capacity); *I* (amounts of SI); *i* (internal rate of return); K_s (saturated hydraulic conductivity); n_p (project lifetime); NRMSE (normalized root mean square error); oi (observed values); $\bar{o}$ (average of observed values); *P* (present value); pi (simulated values); P_c (crop price); P(C) (yield price); P(I) (water price); P/ET_O (precipitations to reference evapotranspiration ratio); PWP (permanent wilting point); ρ_b (bulk density); *R* (annual rainfall, mm); RE (relative error); SI (supplemental irrigation); w_l (optimum irrigation water in land limiting conditions)

Authors' contributions: Design and supervision of the experiments, and critical revision of the manuscript: AAKH, SZP, ARS and FR. Running the model, analysis of data and writing of the paper: MK. Preparation of specific data: MJK. All authors read and approved the final manuscript.

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Introduction

With an approximate 3,370,000 Mg grape production during the last two decades, Iran is the world's third and eighth largest raisin and grape producer, respectively. By providing 17% of the country's total grape yield, Fars province is the main producer in Iran. The province, which is located in the south west of Iran, has an average annual precipitation of 320 mm and an average temperature of about 17°C (Torabi-Haghighi & Keshtkaran, 2008). Due to a severe drought in recent years, rainfed farming in Iran has become difficult. As a result, supplemental irrigation (SI) is necessary to overcome this problem (Tavakoli *et al.,* 2012). In the face of increasing food requirement, various research studies indicate SI for rainfed agriculture as a possible solution (Frone & Frone, 2015; World Bank, 2017).

Soil water availability strongly impacts grapevine growth and its manipulation is key to irrigation management practice. Environmental factors (*e.g.* water stress) and cultivation practices, including irrigation, can affect berry size, quality and yield (Deloire *et al.,* 2004; Poni *et al.,* 2006). Insufficient soil water can lead to water stress in the grapevine, consequently reducing grapevine growth and yields, and can affect the fruit quality, either positively or negatively, depending on the timing and amount of water stress (Pellegrino *et al.,* 2005). In contrast, extra soil water content can lead to too much grapevine vegetative growth, creating a shaded canopy that may be unfavorable to fruit quality and could increase the risk of fungal diseases. In such case, Mazaheri-Tehrani *et al.* (2016) indicated that, for the 'Yaghooti' grapevine cultivar, applying SI during both March and April enhances plant dry matter and less water is stored in the soil for berry production. Therefore, the most important factor in the management of SI is determining both the amount of water used and the most appropriate time for applying it (Mazaheri-Tehrani *et al.,* 2016). Scheduling SI through field experimentation alone is both very difficult and expensive (Rey *et al.,* 2016). However, crop models can be widely used to overcome the problems of agricultural management.

Nowadays, crop simulation models are receiving more attention because of their ability to analyze the response of agricultural systems for different weather and geographical conditions. A model for simulating dry matter production of apples (Lakso *et al.,* 2001) was applied as a base to determine leaf area and dry matter in grapevines (Lakso & Poni, 2005; Poni *et al.,* 2006). This approach, which proved to be easy to apply, presented quite an equitable prediction of leaf area, biomass and carbon balance (Poni *et al.,* 2006; Lakso *et al.,* 2008). The cropping system simulation model (CropSyst) is a common crop growth simulation model that can be widely applied to predict the effect of plant characteristics, soil properties, weather conditions and agricultural practices, including irrigation management related to the growth and yield of both arable and horticultural crops (Stöckle *et al.,* 2003). Recently, the CropSyst model has been adapted for tree crops (Samperio *et al.,* 2014). However, the use of these models requires field experiments to calibrate and validate them for a given region and crop (Cabelguenne *et al.,* 1990; Kropff *et al.,* 1994; Lengnick & Fox, 1994). The CropSyst model has been widely used to predict the influence of climate, soils, and agricultural management on yield, water and nitrogen balance, drought adaptation, and other cropping systems issues at many locations in the world (Stöckle *et al.,* 2003). Eradli (2014) used the CropSyst model to estimate grapevine yields under different climate change scenarios. Samperio *et al.* (2014) used the CropSyst model to successfully predict yield, water use efficiency and crop coefficient for plum trees in Japan. Marsal *et al.* (2013) successfully used the CropSyst model to simulate the yield and crop coefficient of apple trees, while Marsal & Stöckle (2012) used it to regulate irrigation management in a pear orchard. Oyarzun *et al.* (2007) mentioned that, in CropSyst model, canopy light interception and ground cover were calculated by considering daily changes in the size of trees.

'Yaghooti' and 'Askari' grapevines, grown in various regions of Iran, especially in the semi-arid climate of Fars province, are high-income cultivars (Rajaei *et al.,* 2013). These cultivars are very popular Persian grapes that produce small and round fruit with no seed and have a very sweet, juicy, and desirable flavor. SI is necessary to overcome the problem of the recent drought in Fars province (Tavakoli *et al.,* 2012). Previous studies were conducted by Mazaheri-Tehrani (2012), Ghanad (2013) and Kamyab (2014) on the effect of applying supplementary irrigation for rainfed grapevine in experimental fields of School of Agriculture, Shiraz University, but they have not been focused on to what degree the level and timing of SI affects grapevine yield under different climate regions with various weather conditions. Moreover, there has yet been no investigation into the different effects of SI on early ripening and late ripening grape cultivars in arid and semi-arid regions. There is also little understanding of the economic impacts of SI in field scale horticulture, especially for grapevine trees.

Therefore, the main objective of this study is to investigate, by using the CropSyst model, the effect of different SI depths and their application times on rainfed 'Askari' (late ripe cultivar) and 'Yaghooti' (early ripe cultivar) grapevines in different climate regions in Fars province based on the UNESCO aridity index (AI) (UNESCO, 1979). The specific objectives were to: i) calibrate the CropSyst model in the experimental area for rainfed grapevines for different amounts and times of SI application; ii) run the model in the different climate regions of Fars province, in order to estimate the yields of rainfed grapevines under different SI treatments and weather conditions; and iii) conduct an economic analysis of the optimum level of SI for rainfed grapevines under different conditions.

Material and methods

Field experiments

Three years of field experiments in 2012, 2013 and 2014 were conducted in a 40-yr old vineyard located at the School of Agriculture, Shiraz University (long. 52°36´E, lat. 29°43´N, 1810 masl), which was rejuvenated (*i.e.,* restoration of grape production by pruning, which yields younger stems), in order to investigate the effects of different times and amounts of supplemental irrigation on rainfed grapevine (‘Askari’ and ‘Yaghooti’ cultivars) in different climate regions of Fars Province. It is noted that the previous studies were also conducted by Mazaheri-Tehrani (2012), Ghanad (2013) and Kamyab (2014) in the vineyard mentioned above to study the effect of supplemental irrigation on rainfed grapevine just for specific climatic conditions of the experimental area, not for different climate regions. In this study the experimental area is situated in the central region of Fars province with a semi-arid climate. The mean annual precipitation is about 320 mm, the relative humidity is 50%, and the average monthly temperature is 16.8 °C, ranging from 4.7 °C to 29.2 °C. The mean daily maximum and minimum air temperatures and monthly rainfall for each growing season in the experimental area are given in Table S1 [suppl.].

The experiment was conducted taking into account two factors. The first one, named as SI depth, was constituted by four different amounts of SI treatments, being: I1=250 L (35 mm), I2=500 L (70 mm), I3=1000 L (140 mm), and I4=0 L (no SI). The second factor was the SI time, where five different times were trialed, being: T1=single SI in March 25th; T2=single SI in April 25th; T3=single SI in March 25th + single SI in April 25th; T4=single SI in May 15th; and T5=single SI in June 15th. The SI times coincided to different growing stage of grapevine (Table 1). Thus, 20 treatments for ‘Askari’ grapevine and 20 treatments for ‘Yaghooti’ grapevine (15 treatments with SI plus 5 treatments without SI), with three replications (each replicate contained one vine) were obtained in a completely randomized design. There was one embankment (basin) around each grapevine tree (radius 1.5 m and height 0.20–0.28 m), to which the irrigation water was applied. The rainfed vineyard had an area of approximately 12 ha. One hundred and twenty basins, each one with a slope of 5–6%, were built in a sandy clay soil. Inter- and intra-row spacing was 3 m and 3 m, respectively. The grapevines management in the experimental area was organic and no fertilizer was applied.

In order to prevent the invasion of any irrigation treatment on nearby treatments, and to avoid any interference by the irrigated basins along and across the rows, every other grapevine was chosen for treatment, with the result that the treated grapevines were 6.0 m apart (Mazaheri-Tehrani *et al.,* 2016). Soil water content was determined by a neutron probe device (model CPN 503 DR) positioned near to each grapevine with a 30-day interval (except one measurement of a 20-day interval) after each SI event at March 26th, April 26th, May 16th and June 16th, during the three experimental years in all treatments at 0–30, 30–60, and 60–90 cm depths. In three years of experiment at harvest time (six days after maturity as mentioned in Table 1), all of the bunch of grapes in each vine were harvested and weighed directly by digital balance.

Table 1. Average phenological stages of ‘Askari’ and ‘Yaghooti’ grapevines in the three experimental years

	Phenological stage	‘Yaghooti’	‘Askari’
2012	Bud break	20 March	2 April
	Vegetation	20 March to 13 May	2 April to 13 May
	Flowering and fruit set	13 May to 2 June	13 May to 10 June
	Veraison	2 June to 25 June	10 June to 18 July
	Maturity	10 Jul	11 August
2013	Bud break	22-March	5 April
	Vegetation	22- March to 12 May	5 April to 16 May
	Flowering and fruit set	12 May to 4 June	16 May to 13 June
	Veraison	4 June to 28 June	13 June to 20 July
	Maturity	10-Jul	10 August
2014	Bud break	23-March	3-April
	Vegetation	23- March to 10- May	3 April to 12 May
	Flowering and fruit set	10 May to 3 June	12 May to 15 June
	Veraison	3 June to 27 June	15 June to 22 July
	Maturity	12-Jul	13 August

The CropSyst model

The CropSyst model is a daily time step crop growth simulation model, widely used for multi-year and multi-crop (Stockle *et al.,* 1994) agriculture. A general description of the model is provided below (Stockle & Nelson, 1994). The water budget in the model includes precipitation, irrigation, runoff, rain interception, water infiltration, and water redistribution in the soil profile, crop transpiration, and evaporation. Water redistribution in the soil is performed by a simple cascading approach or by a finite difference approach to determine soil water fluxes. This model calculates ET_O by three equations based on the availability of weather information. In decreasing order of required weather data input, these options are: the Penman-Monteith equation, the Priestley-Taylor equation, and a simpler implementation of the Priestley-Taylor equation which only requires air temperature. The Crop ET is determined from a crop coefficient at full canopy and ground coverage determined by the canopy leaf area index. Crop development is simulated based on the thermal time required to reach specific growth stages. The accumulation of thermal time may be accelerated by water stress. Daily crop growth is expressed as biomass increase per unit ground area. A manual of the CropSyst, with a full description of input parameters and file management, is available at http://modeling.bsyse.wsu.edu/CS_Suite/cropsyst/manual/index.html and also the brief flowchart of the CropSyst model is available at https://www.researchgate.net/figure/Flowchart-of-CropSyst-model_fig4_319196782 (Nagamani & Nethaji Mariappan, 2017).

The input parameters of this model include the following (Stockle *et al.,* 1994): soil data that define the properties of soil in each layer; weather information including data regarding daily precipitation, minimum and maximum temperatures, sunshine hours, radiation, relative humidity, and wind speed; and crop parameters that represent the crop's growth and water uptake in the roots.

The crop parameters were retrieved from the CropSyst manual (Stockle & Nelson, 1994) or based on the values measured in the experiments.

Irrigation management in the CropSyst model includes: time and amount of water application; salinity or chemical content of the water; fertilization; tillage; and residue management.

The CropSyst model version 4.13.09 was first calibrated during 2012 and then validated for 2013 and 2014 using both the 'Askari' and 'Yaghooti' grape yield data obtained from the experimental site and based on the treatments which were defined in the experimental site. The daily meteorological data were obtained from a weather station in the College of Agriculture, Shiraz University, located 1 km far from the experimental site. The soil physical and chemical characteristics at the experimental site were determined in the laboratory of Shiraz University (Table S2 [suppl.]).

Model evaluation was conducted by comparing the estimated outputs with the observed values by using three statistical methods:

1. The normalized root mean square error (NRMSE) method was calculated as follows:

$$\text{NRMSE} = \left[\sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(o_i - p_i)^2}\right]/\bar{o} \quad (1)$$

The model is in good agreement when the NRMSE tends towards zero.

2. The Wilmot (Wilmot, 1982) index of agreement (d), is as follows:

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(p_i - o_i)^2}{\sum_{i=1}^{n}(|p_i - \bar{o}| + |o_i - \bar{o}|)^2}\right] \quad (2)$$

Good agreement is indicated when the index tends towards one.

3. Relative error (RE) is defined as the absolute error (observed value – predicted value) relative to the value of the measured parameters (observed).

$$RE = \frac{o_i - p_i}{o_i} \times 100 \quad (3)$$

In these equations, oi and pi are the observed and simulated values, respectively, n is the number of observations and $\bar{o}$ is the average of observed values.

Simulation of rainfed grapevine yield in different regions under some precipitations to reference evapotranspiration ratios (P/ET_O)

In order to simulate rainfed grapevine yields (cvs. 'Askari' and 'Yaghooti') under different weather conditions, eight areas, considered as the main grapevine cultivation regions in Fars province, were selected. These areas had a different aridity index (AI=P/ETo; UNESCO, 1979) according with Sadeghi *et al.* (2002). In this case, Ghasemi *et al.* (2008) modeled the averaged long-term climatic data for the delineation of agro-climate zoning. These authors showed that regions with aridity indices of more than 0.5 are categorized as humid zones, whereas regions with aridity indices of more than 0.65 are mostly covered by forests. In this study the climate zones were divided into arid (AI<0.2), semi-arid (0.2<AI<0.6) and sub-humid (0.6<AI<0.75) regions (Table 2). Fig. S1 [suppl.] shows the location of the eight study areas in Fars province.

The calibrated model parameters were also tested for the average rainfed grapevine yields in each study region, collected by the agricultural organization of Fars province, for a nine-year period from 2008 to 2016.

Financial analysis of optimum level of SI: Conceptual model

Following validation of the model's satisfactory performance, the rainfed grapevine yield for both cultivars, and for each regional group of P/ET_O ratio, was simulated using daily meteorological data from 1990 to 2015 obtained from weather stations placed in the study regions, and their soil properties obtained from the Agricultural Organization of Fars province (Table 2).

Multiple regression equations between the simulated yields and annual effective rainfall + SI (based on irrigation treatment), for each P/ET_O group were individually obtained to simplify yield estimation under different weather conditions. These multiple regressions were also used as the grape production functions for the economic analysis of optimum levels of SI for grapevine trees.

In order to conduct a financial analysis of SI for rainfed grapevines, the land limiting condition method presented by English (1990) was used to determine the optimum SI depth that can be applied for rainfed 'Yaghooti' and 'Askari' grapevine.

The net profit from irrigation optimization was determined by the amount of water applied, the type of crop production function, and the variable and fixed costs of irrigation, water and crop price (Sepaskhah & Akbari, 2005). However, the amount of water applied may be complemented by annual precipitation, which is a variable parameter in different years. The amount of irrigation water in land limiting conditions (w_l) for optimizing the net profit in the presence of rainfall was presented by English & James (1990) and English (1990) as follows:

$$y(I+R) = a_1 + b_1(I+R) + c_1(I+R)^2 \quad (4)$$

$$C(I) = a_2 + b_2 I \quad (5)$$

$$w_l = \frac{b_2 - P_c b_1}{2P_c c_1} - R \quad (6)$$

where a_1, b_1, c_1, a_2 and b_2 are constants; I is the amounts of SI (mm); R is the annual rainfall (mm); $y\ (I+R)$ is the yield per unit of land in kg ha^{-1}, expressed as a function of $(I+R)$; $C(I)$ is the production costs per unit of land in USD ha^{-1}; and P_c is the crop price in USD kg^{-1} collected from the Agricultural Organization of Fars province.

In the production cost function [Eq. (5)], the intercept of the equation consists of the cost of land preparation and planting, which was considered as fixed costs, as well as the cost of pesticides, fertilizer, herbicides, harvest, thinning, land rent and transportation, all of which are considered as annual costs, while the water cost for SI is the slope of this function as a variable cost. The fixed costs were converted to annual costs as follows:

$$CA = P\left(\frac{i}{1-(1+i)^{-n_p}}\right) \quad (7)$$

where CA is the annual uniform production cost and P is its present value, i (15%) is the internal rate of return, and n is the project lifetime which, in this study, was considered to be 30 years.

Table 2. Weather and soil (depth of 0-90 cm in average) characteristics for the eight study areas

Study regions	Neyriz	Darab	Firuzabad	Eghlid	Kazeroon	Nurabad-Mamasani	Shiraz	Sepidan
FC (cm^3 cm^{-3})	0.32	0.32	0.3	0.31	0.32	0.32	0.33	0.33
PWP (cm^3 cm^{-3})	0.19	0.19	0.17	0.17	0.18	0.17	0.19	0.19
ρ_b (g cm^{-3})	1.41	1.42	1.38	1.43	1.39	1.4	1.43	1.3
Organic matter (%)	1%	-----	1.5%	2%	------	-----	2%	----
pH	8.5	8	8	8.2	8.1	8	8.3	8.1
EC (dS m^{-1})	0.68	0.69	0.6	0.58	0.6	0.6	0.6	0.51
Max. temp. (^{o}C)	29	29.8	26.7	19.6	30.1	29.5	25.9	19.9
Min. temp. (^{o}C)	12.2	14.4	1s 4.4	6.2	15.6	12.7	10.2	9.7
Average temp. (^{o}C)	19.4	22.1	20.6	13	23.03	21.1	18.2	15.01
Annual precipitation (mm)	202	249	338.2	260	370	500	315.8	790
Reference evapotransp. (mm)	1927	1730	1606	1301	1638	1502	1481	1209
P/ET_O Group	$P/ET_O<0.2$		$0.2<P/ET_O<0.6$					$P/ET_O>0.6$

FC, field capacity. PWP, permanent wilting point. ρb, bulk density. pH, acidity. EC, electrical conductivity. P/ET_O, ratio of precipitation to reference evapotranspiration.

The production cost functions for each group of P/ET_O ratio and grapevine cultivar are presented in Table 3.

Statistical analysis

Forty treatments and its three replications were distributed in a completely randomize design in three years of experiments. The statistical analysis was conducted using MSTATC software (Plant and Soil Science Department, Michigan State University). The ANOVA analyses were used to examine the effect of four amounts of SI treatments (I1, I2, I3 and I4) and five SI times (T1, T2, T3, T4 and T5) on rain fed grapevine yield and the Duncan's multiple range test for pairwise comparison.

Results

Model calibration and validation

The input crop parameters used for calibrating the CropSyst model are shown in Table 4. The measured and simulated 'Askari' and 'Yaghooti' yields for calibration (2012) and validation (2013 and 2014) processes in the experimental areas are presented in Table 5. The measured yields show that SI in May (T4A & T4Y) increased yields for all amounts of SI treatments compared to those obtained from the single SI application treatments (T1A & T1Y), (T2A & T2Y), and (T5A & T5Y). This was due to the fact that application of SI in May coincides to the flowering and fruit set stage of grapevine (Table 1), when berries begin to enlarge in size.

As it is shown in Table 5, treatment T3A (single SI in March + single SI in April) for all amounts of SI treatments, resulted in a positive effect on the measured 'Askari' grape yields (late ripening cultivar) in comparison with other treatments. However, the effect of treatment T3Y was negative on the measured 'Yaghooti' grape yields (early ripening cultivar).

A comparison of trends between the measured and simulated yields (with the exception of the T3Y treatment) indicated that the CropSyst model is able to accurately simulate the behavior of SI application on grape yield (see Table 5). However, this model fails to correctly simulate the negative effect of treatment T3Y on the 'Yaghooti' grapevine yield. As shown in Table 5, the measured 'Yaghooti' grape yield in this treatment was lower; however, the simulated yield was higher than other treatments.

Figs. 1a to 1f show the relationship between the measured and simulated yields in the calibration and validation processes compared with line 1:1. The scattering of the points around the 1:1 line, the straight-line equation, and the high coefficient of determination (R_2), shows that the model simulated grain yield with a high degree of reliability. In the calibration stage, as illustrated in Figs. 1a and 1d, the NRMSE and d values between the measured and simulated yields for all treatments in 'Askari' were 0.12 and 0.97, respectively, and for single SI treatments in 'Yaghooti' were 0.11 and 0.97, respectively. In the validation process, Fig. 1b and 1c in 'Askari' for all treatments, and Figs. 1e and 1f in 'Yaghooti' for single SI treatments, showed that the simulated and measured data in validation stage agreed very well for the two cultivars with the acceptable values of NRMSE and d.

The measured and simulated data related to T3Y in 'Yaghooti' grapevine are not shown in Figs. 1d, 1e and 1f and neither were taken into account to NRMSE and d calculations due to the fact that the Cropsyst model was not able to simulate the adverse effect of applying the large amounts of SI during the vegetation stage of this

Table 3. Annual cost function for 'Askari' and 'Yaghooti' grapevines at the different values of precipitation to reference evapotranspiration ratios (P/ET_O)

P/ET_O index	Production cost function for 'Askari'	
P/ETo>0.6	C(I)=3.21 (I)+600	Water cost=0.47 USD m^{-3}
0.2<P/ETo<0.6	C(I)=4.67(I) +300	Water cost=0.83 USD m^{-3}
P/ETo<0.2	C(I)=5.81(I)+300	Water cost=0.95 USD m^{-3}
	Production cost function for 'Yaghooti'	
P/ET_O>0.6	C (I)=5.32 (I)+550	Water cost=0.95 USD m^{-3}
0.2<P/ETo<0.6	C (I)=6.24 (I)+275	Water cost=1.42 USD m^{-3}
P/ETo<0.2	C (I)=7.38 (I)+275	Water cost=1.90 USD m^{-3}

C(I) is the annual production costs per unit of land in USD ha^{-1}. (I) is the amount of supplemental irrigation (mm)

Table 4. Crop parameters for 'Askari' and 'Yaghooti' grapevines

Parameters	Activity	'Yaghooti'	'Askari'
Base temp (°C)	Experimental data[1]	10	10
Cut-off temp (°C)	Experimental data[1]	35	30
Evapotranspiration crop coefficient at full canopy	Observed	1	0.8
Canopy extinction coefficient for total solar radiation	Default	0.5	0.5
Leaf water potential at the onset of stomata closure (J/kg)*	Calibration	-1300	-1000
Wilting leaf water potential (J/kg)*	Calibration	-2000	-1500
Max. water uptake (mm/day)*	Calibration	12	12
Maximum expected leaf area index	Default	5	5
Specific leaf area at optimum temp (m^2 kg^{-1})*	Calibration	22	22
Stem/leaf partition coefficient*	Calibration	3	4
End of vegetative growth (°C-days)*	Observed	310	390
Beginning of flowering (°C-days) *	Observed	400	530
Beginning of filling (°C-days)*	Observed	540	680
Beginning of rapid fruit growth (°C-days)*	Observed	700	1020
Physiological maturity (°C-days)*	Observed	850	1200
Maximum root depth (m)	Experimental data[1]	3	2.5
Root length per unit root mass (km kg^{-1})	Default	40	40
Day of year to start searching for beginning of dormancy	Observed	270	270
Dormancy threshold temperature (°C)	Default	5	5
Fruit tree chill requirement (number of hours below 10 °C)	Default	100	100
Root sensitivity to water stress	Calibration	0.2	0.2

*The most important variables in the CropSyst model in this study. [1] Mazaheri-Tehrani (2012); Ghanad (2013) and Kamyab (2014).

Table 5. Measured and simulated 'Askari' and 'Yaghooti' grape yields for a three-year period in the experimental area

	'Yaghooti' grapevine yield (×1000 kg ha^{-1})					'Askari' grapevine yield (×1000 kg ha^{-1})				
	Treatments[A]		Observed	Simulated	Relative error (%)	Treatments[A]		Measured	Simulated	Relative error (%)
2012 (Calibration)	T1Y	I1Y	1.53±0.020ghi[B]	1.45 n	5.00	T1A	I1A	1.46±0.014j	1.45 l	0.68
		I2Y	1.61±0.050fg	1.63 l	1.00		I2A	1.55±0.020j	1.55 i	0.00
		I3Y	1.86±0.070f	1.88 j	1.00		I3A	1.94±0.040g	1.72 g	11.34
		I4Y	1.30±0.040i	1.33 o	2.00		I4A	1.20±0.020j	1.44 l	20.00
	T2Y	I1Y	1.92±0.040e	2.09 i	9.00	T2A	I1A	1.53±0.030j	1.79 j	17.00
		I2Y	2.48±0.040d	2.19 h	12.00		I2A	1.81±0.030g	1.86 i	2.76
		I3Y	2.15±0.050e	2.44 g	13.00		I3A	2.35±0.020e	2.37 e	0.85
		I4Y	1.39±0.030ghi	1.33 o	4.00		I4A	1.38±0.020j	1.44 l	4.35
	T3Y	I1Y	1.45±0.060ghi	2.98 d	106.00	T3A	I1A	2.94±0.040c	2.66 c	9.52
		I2Y	1.57±0.070fg	3.28 b	109.00		I2A	3.13±0.027b	2.91 b	7.03
		I3Y	1.39±0.050ghi	3.89 a	180.00		I3A	3.27±0.021a	3.13 a	4.28
		I4Y	1.44±0.050i	1.33 o	8.00		I4A	1.22±0.022j	1.44 l	18.00
	T4Y	I1Y	2.89±0.050c	2.66 f	8.00	T4A	I1A	1.77±0.030h	1.56 i	12.00
		I2Y	3.32±0.040b	3.92 e	18.00		I2A	2.17±0.020f	1.93 f	11.00
		I3Y	3.70±0.050a	3.17 c	14.00		I3A	2.85±0.020d	2.31 d	19.00
		I4Y	1.32±0.020i	1.33 o	1.00		I4A	1.21±0.016j	1.44 l	19.00
	T5Y	I1Y	1.42±0.060ghi	1.50 m	6.00	T5A	I1A	1.42±0.020j	1.45 l	2.11
		I2Y	1.48±0.030ghi	1.46 n	1.00		I2A	1.51±0.021j	1.48 jk	2.00
		I3Y	1.62±0.050fgh	1.66 k	2.00		I3A	1.87±0.032h	1.66 h	11.23
		I4Y	1.32±0.070hi	1.33 o	1.00		I4A	1.19±0.026j	1.44 l	21.00

Table 5. (Continued)

	'Yaghooti' grapevine yield (×1000 kg ha^{-1})					'Askari' grapevine yield (×1000 kg ha^{-1})				
	Treatments[A]		Observed	Simulated	Relative error (%)	Treatments[A]		Measured	Simulated	Relative error (%)
2013 (Calibration)	T1Y	I1Y	1.29±0.020ghi[B]	1.20 n	7.00	T1A	I1A	1.13±0.015j	1.30 l	15.00
		I2Y	1.35±0.050fg	1.38 l	2.00		I2A	1.27±0.020j	1.40 i	10.24
		I3Y	1.57±0.070f	1.64 j	4.00		I3A	1.51±0.050g	1.57 g	4.00
		I4Y	1.10±0.040i	1.08o	2.00		I4A	1.15±0.020j	1.21 l	5.22
	T2Y	I1Y	1.75±0.040e	1.84 i	5.00	T2A	I1A	1.22±0.021j	1.34 j	9.84
		I2Y	2.15±0.040d	1.94 h	10.00		I2A	1.45±0.030g	1.41 i	2.76
		I3Y	1.87±0.050e	2.17 g	16.00		I3A	1.81±0.023e	1.92 e	6.00
		I4Y	1.16±0.030ghi	1.08 o	7.00		I4A	1.23±0.025j	1.21 l	1.63
	T3Y	I1Y	1.35±0.060ghi	2.42 f	79.00	T3A	I1A	2.35±0.050c	2.51 c	6.81
		I2Y	1.51±0.070fg	2.67 e	77.00		I2A	2.60±0.030b	2.76 b	6.00
		I3Y	1.23±0.050ghi	2.93 c	138.00		I3A	2.81±0.026a	2.96 a	5.34
		I4Y	1.17±0.050i	1.08 o	8.00		I4A	1.15±0.020j	1.21 l	5.22
	T4Y	I1Y	2.83±0.050c	2.72 d	4.00	T4A	I1A	1.37±0.010h	1.41 i	2.92
		I2Y	3.10±0.040b	3.08 b	1.00		I2A	1.61±0.025f	1.77 f	10.00
		I3Y	3.56±0.050a	3.67 a	3.00		I3A	2.27±0.026d	2.16 d	4.85
		I4Y	1.15±0.020i	1.08 o	6.00		I4A	1.18±0.014j	1.21 l	2.54
	T5Y	I1Y	1.34±0.060ghi	1.29 m	4.00	T5A	I1A	1.19±0.021j	1.30 l	9.24
		I2Y	1.39±0.030ghi	1.21 n	13.00		I2A	1.22±0.025j	1.33 jk	9.00
		I3Y	1.53±0.050fgh	1.43 k	7.00		I3A	1.37±0.030h	1.51 h	10.22
		I4Y	1.12±0.070hi	1.08 o	4.00		I4A	1.13±0.022j	1.21 l	7.00
2014 (Validation)	T1Y	I1Y	1.16±0.090ghi[B]	1.13 n	2.59	T1A	I1A	1.16±0.150j	1.12 l	3.45
		I2Y	1.21±0.060fg	1.31 l	8.26		I2A	1.20±0.050j	1.28 i	6.67
		I3Y	1.41±0.102f	1.55 j	9.93		I3A	1.45±0.040g	1.43 g	1.4
		I4Y	1.03±0.060i	1.07 o	3.88		I4A	1.12±0.050j	1.10 l	1.8
	T2Y	I1Y	1.58±0.030e	1.75 i	10.76	T2A	I1A	1.20±0.120j	1.19 j	0.83
		I2Y	1.92±0.060d	1.89h	1.56		I2A	1.39±0.070g	1.26 i	9.35
		I3Y	1.60±0.080e	2.12 g	32.5		I3A	1.75±0.040e	1.78 e	1.71
		I4Y	1.04±0.060ghi	1.07 o	2.88		I4A	1.17±0.050j	1.10 l	6
	T3Y	I1Y	1.17±0.080ghi	2.63d	124	T3A	I1A	2.31±0.070c	2.40 c	4
		I2Y	1.32±0.090fg	2.95 b	123		I2A	2.52±0.060b	2.63 b	4.4
		I3Y	1.10±0.030ghi	3.51 a	219		I3A	2.75±0.030a	2.81 a	2.2
		I4Y	1.00±0.080i	1.07 o	7		I4A	1.19±0.100j	1.10 l	7.55
	T4Y	I1Y	2.66±0.070c	2.31 f	13.16	T4A	I1A	1.29±0.090h	1.25 i	3.10
		I2Y	2.97±0.090b	3.59e	20.88		I2A	1.53±0.030f	1.51 f	1.31
		I3Y	3.25±0.030a	2.81 c	13.54		I3A	2.19±0.020d	2.02 d	7.8
		I4Y	0.98±0.120i	1.07 o	9.18		I4A	1.18±0.012j	1.10 l	6.8
	T5Y	I1Y	1.27±0.090ghi	1.31m	3.15	T5A	I1A	1.24±0.120j	1.11 l	10.5
		I2Y	1.31±0.070ghi	1.22n	6.87		I2A	1.27±0.040j	1.22 jk	4
		I3Y	1.47±0.080fgh	1.35 k	8.16		I3A	1.31±0.050h	1.36 h	4
		I4Y	1.17±0.060hi	1.07 o	8.55		I4A	1.12±0.030j	1.10 l	1.8

[A] Supplemental irrigation during: March (T1Y and T1A), April (T2Y and T2A), March and April (T3Y and T3A), May (T4Y and T4A), and June (T5Y and T5A); and supplemental irrigation depth equal to 250 L (I1Y and I1A), 500 L (I2Y and I2A), 1000 L (I3Y and I3A), and no supplemental irrigation (I4Y and I4A). [B] Means followed by the same letters in columns for each factor are not significantly different at 5% level of probability, using Duncan's multiple range test.

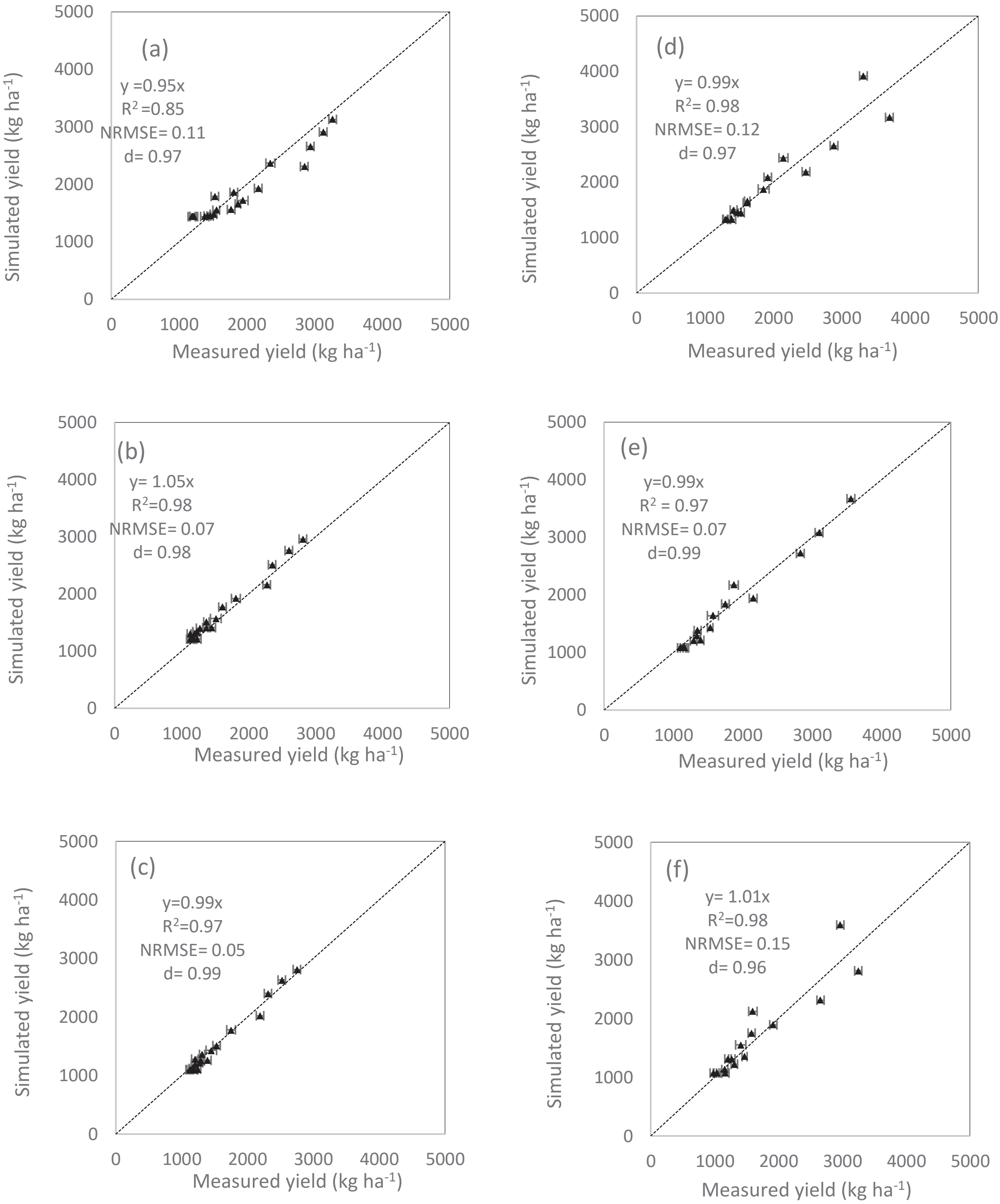

Figure 1. Relationship between the measured and simulated grapevine yields in the experimental area. (a), (b) and (c): 2012 (calibration), 2013 (validation) and 2014 (validation), respectively for all treatments in 'Askari' cultivar; (d), (e) and (f): 2012 (calibration), 2013 (validation) and 2014 (validation), respectively for single SI treatments in 'Yaghooti' cultivar.

Table 6. Summary of statistical analysis for model test in rainfed conditions (no supplemental irrigation) in the study regions, 2008-2016

	Sepidan	Shiraz	Nurabad-Mamasani	Kazeroon	Eghlid	Firuzabad	Darab	Neyriz
NRMSE	0.08	0.17	0.17	0.15	0.13	0.05	0.17	0.14
d	0.90	0.96	0.87	0.96	0.95	0.99	0.99	0.92

early ripening cultivar and consequently it was not able to accurately simulate T3Y yield.

Simulation of the rainfed grapevine yield in different P/ET_O groups

The values of the NRMSE and d between the measured and simulated yield are shown in Table 6 in the validation stage for the study regions. The minimum and maximum values of the NRMSE and d are 0.08 to 0.17 and 0.9 to 0.99, respectively, and it is clear that the measured and simulated yields are in good agreement each other.

Fig. 2 shows the simulated 'Askari' and 'Yaghooti' yields, respectively, in different P/ETo groups. Comparing the grapevine yield between treatments by one-time SI application indicated that the SI in May (treatments T4A&T4Y) significantly increased the grape yield in comparison with those obtained in the T1A & T1Y, T2A & T2Y, and T5A & T5Y for all amounts of SI application treatments. As shown in Figs. 2a to 2c, the mean grapevine yield for 'Askari' for all amounts of SI application treatments obtained from treatment T4A was about 14% at P/ET_O>0.6, 27% at 0.2<P/ET_O<0.6 and 17% at P/ET_O<0.2, which was higher than the average grapevine yields obtained from treatments T1A, T2A and T5A. Furthermore, the two-time applications of SI for 'Askari' in both March and April (treatment T3A) significantly increased the average simulated grape yield for all amounts of SI applications, approximately 12% at P/ET_O>0.6, 14% at 0.2<P/ET_O<0.6 and 21% at P/ET_O<0.2 compared with the T4A treatment (see Fig. 2). The results in Figs. 2a to 2c show that, in the case of 'Askari', for all SI application times and amounts, there was a mean yield increase of about 25%, 31% and 45% for the P/ET_O>0.6, 0.2<P/ET_O<0.6 and P/ET_O<0.2 areas, respectively, compared with the I4A (no SI) treatment. The results also indicate that in most cases the difference between the grapevine yield in T1A, T2A and T5A in each amount of SI treatment and also the difference between the grapevine yield in treatment I4A and the treatments T1A, I1A and T5A I1A were not significant in all P/ET_O group. Figs. 2d to 2f shows that for the treatment T4Y, there was a significant mean yield increase of about 14% at P/ET_O>0.6, 19% at 0.2<P/ET_O<0.6 and 21% at P/ET_O<0.2 compared with average yields obtained from treatments T1Y, T2Y and T5Y. However, the differences between the 'Yaghooti' yield in T3Y and T4Y treatments were not significant. As the results indicated, the mean percentage of increase in the 'Yaghooti' yield for treatment T3Y for all amounts of SI application treatments was only about 2% compared with treatment T4Y. The results also indicate that in the study regions with 0.2<P/ET_O<0.6 and P/ET_O<0.2 the differences between the yield in I4Y and T1Y I1Y and T5Y I1Y were not significant. The results from Figs. 2d to 2f show that, in the case of 'Yaghooti', there was a mean yield increase for all SI times and amount treatments of about 22%, 26% and 35% for the P/ET_O>0.6, 0.2<P/ET_O<0.6 and P/ET_O<0.2 areas, respectively, compared with the I4Y (no SI) treatment. Additionally, by increasing the amount of SI application in each treatment, the yields for the two grapevine cultivars were increased.

Multiple regressions between the simulated grape yield and the effective rainfall + SI in each P/ET_O group were obtained to simplify yield estimation under different annual precipitation and SI conditions (Table 7). In all equations, a coefficient of determination R^2>0.8, and a p<0.05, indicate that these multiple regressions can estimate the grape yield with a high level of accuracy. Furthermore, the second order polynomial equations indicate that the grape yield at first increases by increasing irrigation + rainfall, up to a maximum potential yield, after which it decreased by increasing irrigation + rainfall due to water logging, nutrient leaching and possible disease as a result of extra soil water content in the plant root zone. In the case of 'Askari', the maximum potential yields for P/ET_O>0.6, 0.2<P/ET_O<0.6 and P/ET_O<0.2 were about 6700 kg ha^{-1}, 4900 kg ha^{-1} and 3960 kg ha^{-1}, respectively. Similarly, for 'Yaghooti', the maximum yields at P/ET_O>0.6, 0.2<P/ET_O<0.6 and P/ET_O<0.2 were about 4300 kg ha^{-1}, 3600 kg ha^{-1} and 2900 kg ha^{-1}, respectively.

Soil water content simulation

Variation of mean volumetric soil water content at 0–90 cm depth during three growing seasons for all times and amounts of SI are shown in Figs. 3a to 3e. The values of the NRMSE and d between the simulated and observed parameters were 7% and 0.97 respectively, which show a good agreement between the simulated and measured volumetric soil water contents. As it is shown in these Figures, the values of soil water content reached to its maximum level at the time of SI application and after that it was decreased gradually until the end of the growing season. The values of soil water content in I1 treatment (1000 L SI) in all times of SI application were higher than those obtained in other treatments (I2, I3 and I4) and decreased by decreasing the amount of SI. The soil water content in all amounts of SI at the end of the growing season had almost the same value except the I4 treatment that had the lowest value of soil water content. As it was shown in Fig. 3d, in treatment T4 the value of soil water content from May 15th to June 15th was higher than those obtained in other single SI treatments (Figs 3a, 3b and 3e), in which this period coincided to the flowering and fruit set stage in both grapevine cultivars (Table 1), and consequently caused a higher grapevine yield in this treatment (T4) as compared to those obtained in other single SI treatments (Table 5). In treatment T3 (single SI in

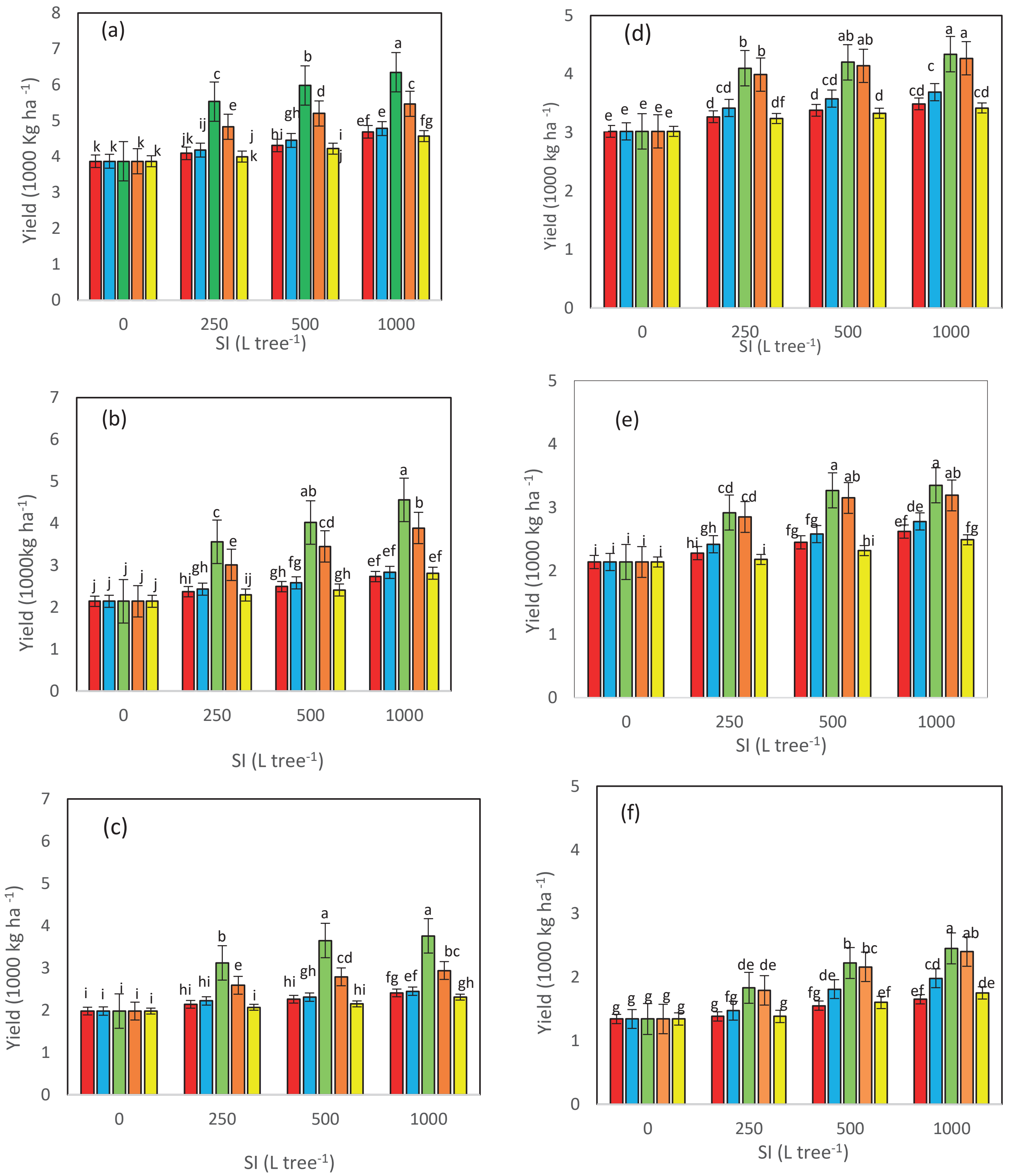

Figure 2. 'Askari' and Yaghooti grapes yield under different SI treatments and average annual precipitation in the study regions, (a): $P/ET_O>0.6$; (b): $0.2<P/ET_O>0.6$; (c): $P/ET_O<0.2$ in Askari cultivar and (d): $P/ET_O>0.6$; (e): $0.2<P/ET_O>0.6$; (f): $P/ET_O<0.2$ in Yaghooti cultivar. Same letters above the histogram bars indicate not significant differences between groups at 5% level of probability

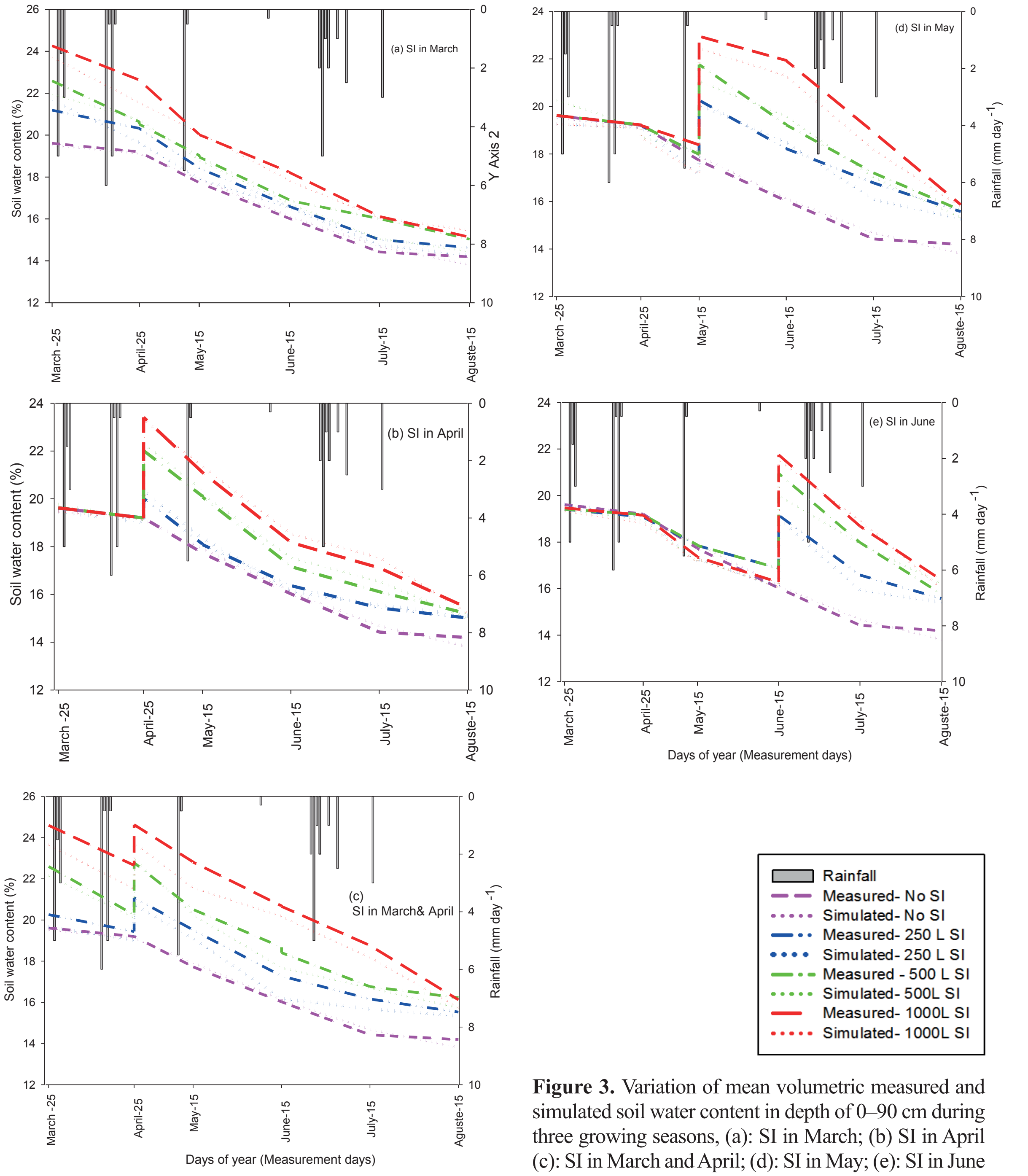

Figure 3. Variation of mean volumetric measured and simulated soil water content in depth of 0–90 cm during three growing seasons, (a): SI in March; (b) SI in April (c): SI in March and April; (d): SI in May; (e): SI in June

Table 7. 'Askari' and 'Yaghooti' grape yield functions for different amounts of annual rainfall plus SI

P/ET$_O$ index	Yield function of 'Askari'	
P/ET$_O$>0.6	Y=-0.0025(R+I)^2+7.2(R+I)+ 680.5	*p*-value=2.52E-6, R^2=0.90
0.2<P/ETo<0.6	Y=-0.0038(R+I)^2+9.82(R+I)- 20.4	*p*-value=2.91E-5, R^2=0.90
P/ETo<0.2	Y=-0.0045(R+I)^2+9.12(R+I)-950.82	*p*-value=1.71E-5, R^2=0.91
	Yield function of 'Yaghooti'	
P/ET$_O$>0.6	Y=-0.0025 (R+I)^2+6.10 (R+I)+24.52	*p*-value=1.9E-6, R^2=0.80
0.2<P/ETo<0.6	Y=-0.0035(R+I)^2+6.40(R+I)+290.15	*p*-value=0.0019, R^2=0.87
P/ETo<0.2	Y=-0.0025(R+I)^2+4.85(R+I)+60.25	*p*-value=0.0002, R^2=0.82

* R and I are the levels of total annual rainfall (mm) and SI (mm), respectively. Y is the 'Askari' and 'Yaghooti' yield (kg ha^{-1})

Table 8. The optimum equations of supplemental irrigation (SI) for 'Askari' and 'Yaghooti' grapevine cultivars under different precipitation to reference evapotranspiration ratios (P/ET_O)

P/ET_O index	Optimum SI value (w_L) equations for 'Askari'		
$P/ET_O>0.6$	w_L=100.40 P(C)-1367.5 P(I)-R+1443.5	p-value=7.89E-33,	R^2=0.93
0.2<P/ETo<0.6	w_L=85.32 P(C)-892 P(I)-R+992.55	p-value=5.48E-41,	R^2=0.93
P/ETo<0.2	w_L=52.60 P(C) -683.76 P(I)-R+755.23	p-value=4.86E-40,	R^2=0.93
	Optimum SI value (w_L) equations for 'Yaghooti'		
$P/ET_O>0.6$	w_L=98.80 P(C)-501 P(I)-R+1252	p-value=6.79E-33,	R^2=0.97
0.2<P/ETo<0.6	w_L=37.50 P(C)-358.3 P(I)-R+867	p-value=4.12E-37,	R^2=0.95
P/ETo<0.2	w_L=17.25 P(C)-282 P(I)-R+674.5	p-value=7.22E-36,	R^2=0.95

P(C) and P (I) are the yield and water price (USD), respectively, R is the annual precipitation (mm) and w_L is the optimum amount of SI (mm)

March 25th + single SI in April 25th) the value of soil water content from March 25th to May 15th [vegetation stage in 'Yaghooti' (Table 1)] remained at high level and as it was mentioned before, it caused high vegetation growth in an early ripening cultivar like 'Yaghooti'.

Economic analysis of SI for grapevines under land limiting conditions

Production and production cost functions

The annual cost and grape production functions for each group of P/ETo ratio and grapevine cultivar are presented in Tables 3 and 7, respectively. The price of water, which varies in each region depending on abundance and ease of access, includes water transportation and application. The slope of production cost functions depends on the price of water while the intercept depends on the fixed and annual costs in each area.

Optimal SI in land limiting conditions

For both 'Askari' and 'Yaghooti' cultivars, Table 8 presents multiple linear equations for obtaining the optimum amount of SI in various effective annual precipitation conditions, different water costs and different selling prices of the harvests. Fig. 4 shows the relationship between the SI (mm) and water cost in different annual precipitation conditions, whereas the SI is essential for benefitting from rainfed grapevines and gaining an acceptable yield. The results show that by increasing annual precipitation as well as water cost, the optimum SI decreases. For the 'Askari' cultivar (Fig. 4a-c) with minimum annual precipitation related to each region (100 mm), the SI is economical when the water price is up to about 0.95 USD m^{-3}. However, for 'Yaghooti' grapevines (Fig. 4e-f) under the same conditions, the water price is up to 1.95 USD m^{-3} for SI to be economically feasible.

Fig. 5 shows the relationship between the net profit and applied SI water at different unit water prices and in the annual 200 mm rainfall, which is less than the average annual precipitation of Fars province. The results indicate that changes in the cost of water affect the profits from SI. Thus, in order to achieve higher net profit, the amounts of optimum SI at a given level of annual precipitation decrease by increasing the price of water. As shown in Fig. 5, by increasing the amounts of SI application, the net benefit increases up to a maximum point for each water price, after which it decreases. These results may be related to the fact that by increasing the amount of SI, the grape yield is also increased and the profit from this increase can compensate for the cost of water. In addition, after the maximum point, the net benefit decreases due to the increase in the water cost that compensates for the benefit attained from the production of a higher yield. The results from Fig. 5 indicate that, by increasing the water price by about 50% and 30%, the average attainable net benefits of all P/ET_O groups for the 'Askari' grapevine cultivar decrease by about 54% and 31%, respectively, while for the 'Yaghooti' cultivar the net benefits decrease by about 18% and 6%, respectively. These results demonstrate that the impact of the cost of water for SI application would be lower by increasing the selling price of the grapevine yield.

The amount of net benefit obtained from 'Askari' and 'Yaghooti' without SI application at the regions by P/ETo>0.6 was the highest (1143 and 1905 USD ha^{-1} for 'Askari' and 'Yaghooti', respectively) due to the production of more grapevine yields in the regions by higher precipitation and lower evapotranspiration. The net benefit in the regions by 0.2<P/ETo<0.6 (762 and 1381 USD ha^{-1}) and P/ETo<0.2, (667 and 1071 USD ha^{-1}) ranked in second and third places, respectively (see Fig. 5). The results also indicate that under the same amount of SI application and annual rainfall, for 'Askari' grapevine in the average optimum SI for each regional group (SI=124 mm in $P/ET_O>0.6$, SI=102 mm in $0.2<P/ET_O<0.6$ and SI=68 mm in $P/ET_O<0.2$), the average net benefit decreased about 15.6% when water cost increased from 0.47 USD

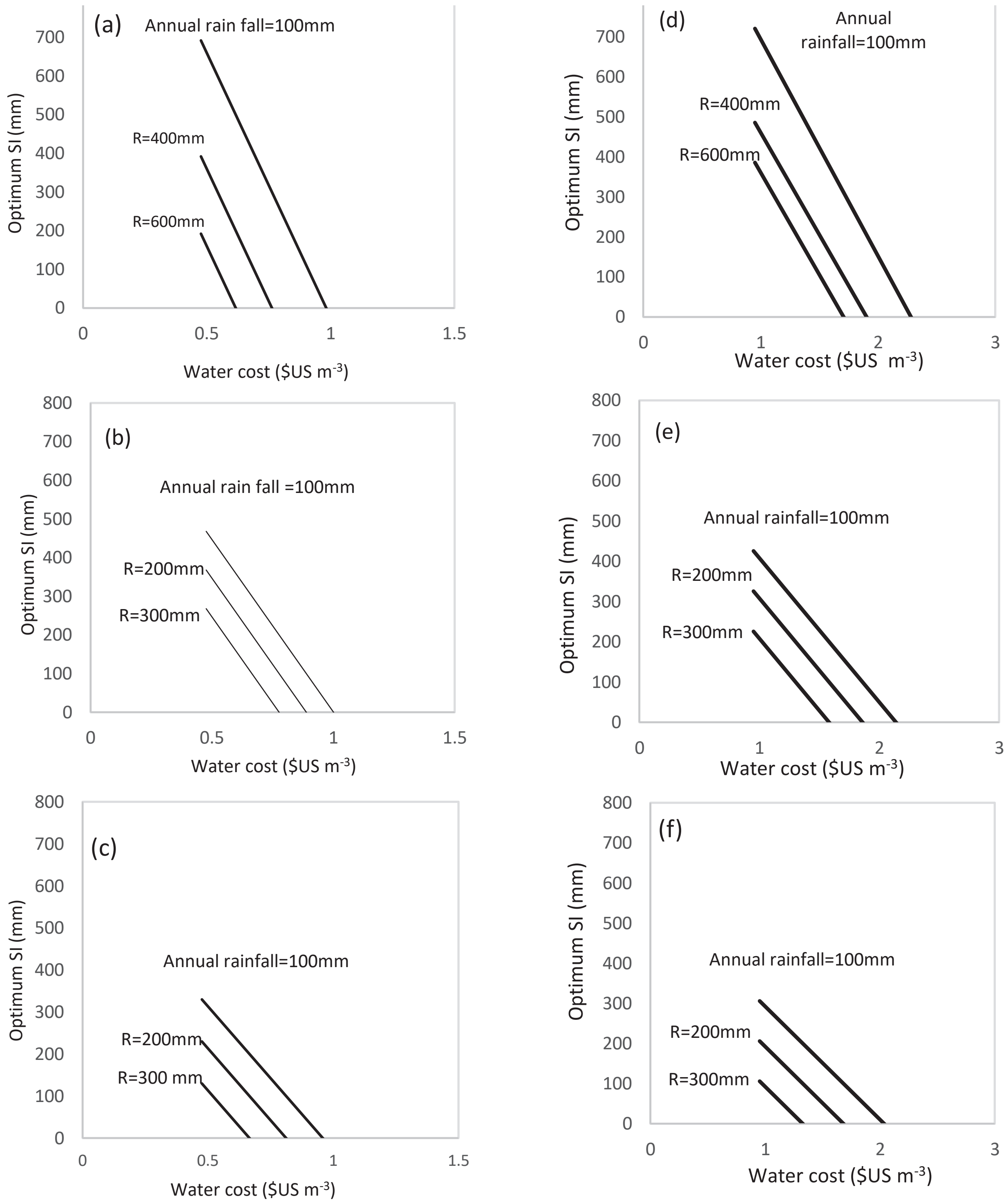

Figure 4. Relationship between the optimum SI (wl) (mm) and water cost (USD m^{-3}) for the 'Askari'and Yaghooti grapes for different annual precipitation levels, (a): P/ETo>0.6; (b): 0.2<P/ETo<0.6; (c): P/ETo<0.2 in cv. 'Askari' and (d): P/ETo>0.6; (e): 0.2<P/ETo<0.6; (f): P/ETo<0.2 in cv. 'Yaghooti'

m^{-3} to 0.95 USD m^{-3} (Fig. 5a-c). For 'Yaghooti', in the average optimum SI for each regional group (SI=160 mm in $P/ET_O>0.6$, SI=112 mm in $0.2<P/ET_O<0.6$ and SI=71 mm for $P/ET_O<0.2$), the average net benefit decreased about 30% when water cost increased from 0.95 USD m^{-3} to 1.9 USD m^{-3} (Fig. 5d-e). The results also indicated that under the same amount of SI application and annual rainfall, the net benefit obtained from 'Yaghooti' was higher than 'Askari' due to the higher selling price of 'Yaghooti'. This indicates that the selling price of the yield can play an important role in the determination of economically feasible SI in rainfed areas.

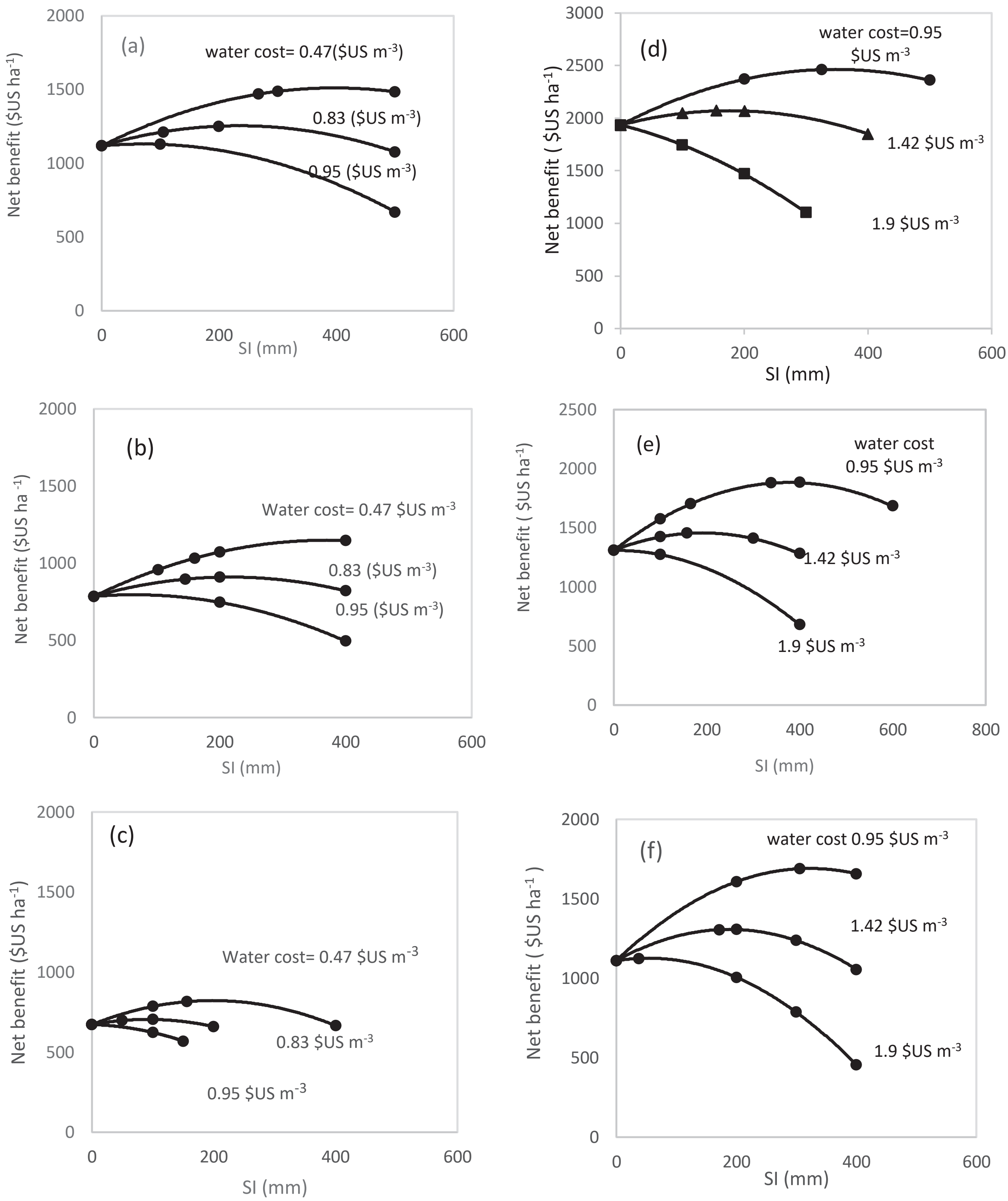

Figure 5. Relationship between net profit and applied SI water for 'Askari' and Yaghooti grapevines at different unit water prices and for the annual precipitation (200 mm). (a): P/ETo>0.6; (b): 0.2<P/ETo<0.6; (c): P/ETo<0.2 in Askari cultivar and (d): P/ETo>0.6; (e): 0.2<P/ETo<0.6; (f): P/ETo<0.2 in Yaghooti cultivar.

Discussion

An analysis of grape yield simulation data indicates that the CropSyst model can be used with a good degree of acceptability in the practical management of SI as well as in the prediction of grape yield with regard to different weather conditions. In this case, Eradli (2014) successfully used the CropSyst model to estimate the grapevine yield under different climate change scenarios. Marsal & Stöckle (2012) reported that the CropSyst model can successfully simulate pear tree water stress in short periods during the growing season. Moreover, Marsal *et al.* (2013) showed that this model can ideally predict crop coefficient for apples. The value of K_c for a full canopy cover is different in 'Yaghooti' and 'Askari'. In this case, Marsal *et al.* (2014) indicated that the $K_{c,fc}$ for deciduous fruit trees is different depending on the cultivar and the time of year. In addition, because these two grapevine cultivars are drought resistant, their root depths are deeper than other grapevine cultivars. Moreover, based on the study of Kamyab (2014) and Mazaheri-Tehrani *et al.* (2016), since 'Askari' is more drought resistant than 'Yaghooti', the root depth in 'Askari' is in fact deeper than in 'Yaghooti'.

The results obtained from the analysis of measured and simulated grapevine yields show that SI can have a positive effect on increasing rainfed grape yield. In such a case, Intrigliolo & Castel (2010) indicated that moderate irrigation (in average 70 mm tree^{-1}) increases grapevine yield by about 12% as compared to that obtained in rainfed treatment. This result is in agreement with the results obtained in this study for 'Yaghooti' under I2 irrigation treatments in average for all time of SI application. Application of SI in May (treatment T4) resulted in enough soil water content in flowering and fruit set stage in both grapevine cultivars (Fig. 3d). This fact caused higher grapevine yield in this treatment as compared to that obtained in other single SI treatments. In treatment T3 (single SI in March 25th + single SI in April 25th) the value of soil water content from the end of March to middle of May remained at high level (Fig. 3c) and caused negative effect on 'Yaghooti' grape yield. However, this effect was positive on 'Askari' yield. The difference between the behavior of these two cultivars under the condition of treatment T3 are due to the difference in their phenological stages (Table 1), such that the growing period of 'Askari' is long enough to use the total amount of water that is saved in the root zone for berry growth and production. However, in 'Yaghooti', since the growing period is short, the trees do not have enough time to completely use the soil water that is saved in the root zone for berry growth and production. Moreover, since the vegetative growth stage of 'Yaghooti' starts from late March to early May (Table 1), the applied SI water in late March and April is directly consumed by the tree to increase the plant dry matter production and, as a result, less water is saved in the root zone for berry production. In this case, several studies show that by using too much irrigation water at the grapevine vegetation stage, vegetative growth and cluster shading are increased and the final color and phenolic content of the grape significantly decreased (Valdés *et al.,* 2009; Basile *et al.,* 2011). Bagheri & Sepaskhah (2014) showed that winter rainfall is the influential parameter for fig yield, but rainfall in spring has an adverse effect on the life cycle of the Caprifig wasp (*Blastophaga psenes* L.).

The overall results from the simulated grapevine yield in the study regions (Fig. 2) indicate that in the regions with low precipitation and high evapotranspiration ($P/ET_O<0.2$), SI was more effective for increasing grapevine yield compared with the regions with high precipitation and low evapotranspiration ($P/ET_O>0.6$). The supplemental irrigation of 250 L tree^{-1} in March and June had no significant effect on increasing the yield in the two cultivars, as the results showed in most of cases there were no significant difference among the yields in I4A, T1AI1A and T5AI1A, and also among the yield in I4Y, T1YI1Y and T5YI1Y treatments. The results showed that there were significant differences between the yield in T3A and T4A treatments, while the differences between the yield in T3Y and T4Y were not significant. The amount of optimum SI for grapevines varied with respect to annual precipitation, water cost, and yield selling price. Therefore, by using the presented equations (Table 8), the optimum level of SI (w_l) to increase grape yield and especially net benefit, can be calculated for different conditions. In these cases, an economic analysis of SI for rainfed fig trees in the south of Iran was conducted by Khozaei & Sepaskhah (2018), the results showed that by decreasing about 55 % of SI, the fig yield decreased about 28% and net income increased twice compared with that obtained in full irrigation condition. The study of fig trees by Tapia *et al.* (2003) shows that, in an area with an annual precipitation of about 37 mm, an approximate amount of 220 mm for SI could generate economic yield. Under the same amounts of SI application, the net benefit obtained for 'Yaghooti' was higher than that obtained for 'Askari' due to the difference between the selling prices of yields, which was higher for 'Yaghooti' than for 'Askari' (1.19 USD kg^{-1} for 'Yaghooti' and 0.47 USD kg^{-1} for 'Askari' in 2018). Also as a result of this difference in selling price, higher-priced water can be used for SI in 'Yaghooti'.

By increasing the water price by about 50% and 30%, the average attainable net benefits of all P/ET_O groups for 'Askari' decreased by about 54% and 31%, respectively, while the net benefits for 'Yaghooti' decreased by about 18% and 6%, respectively.

Combining the results of this study indicated that applying SI in flowering and fruit set stage of rainfed grapevines have a positive effect on both early and late ripening cultivars, while applying SI in vegetation stage of grapevines especially in early ripening cultivars have an adverse effect on grape yield. Also it can be concluded that the impact of increased in water price on the attainable net benefit is lower for high-value crops but, when water prices increase, the viability of SI for low-value crops then decreases, so the selling price of the yield can play an important role in the determination of economically feasible SI in rainfed areas.

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