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EVALUATION OF THE EFFICIENCY OF SURFACE AND SUBSURFACE IRRIGATION IN DRYLAND ENVIRONMENTS†

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ABSTRACT

Irrigation water quantity and quality limitation is the main problem of agricultural development in the research area (Rafsanjan pistachio orchards in Iran). Optimization of the irrigation system is one of the most important factors to enhance water use efficiency in this region. This research project was designed to compare the applicability of two different types of irrigation, including traditionally used surface irrigation and a simple and relatively cheap subsurface drip irrigation (using a perforated pipe covered with plastic cloth). For this purpose two plots, each containing 39 pistachio trees and 720 m^2 in area, were selected in an orchard and were both irrigated using an exactly equal quantity and quality of water for 3 years. At the end of the second year the yield in the plots was harvested separately and compared. The ratio of the weight of fresh and also dried crop in the subsurface irrigation plot to those of surface irrigation plot was respectively 1.895 and 2 for the second year, and 2.17 and 2.12 for the third year. Another parameter measured for the trees of the two plots was annual shoot growth. The value of the plot growth index (PGI) in the surface irrigation plot was calculated as 2238 cm, whereas in the subsurface irrigation plot it was 4580 cm. In addition, the dried weight of weed grown in the surface irrigation plot was 82 kg but was only 21 kg in the subsurface irrigation plot. These results show the considerable difference in efficiency of the two irrigation systems, and relatively higher preference for a subsurface system over the traditionally used surface method. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: subsurface irrigation; irrigation efficiency; pistachio orchards; water use efficiency (WUE); drylands water use; irrigation optimization

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RÉSUMÉ

La limitation en quantité et qualité de l'eau d'irrigation est le principal problème du développement agricole dans la zone de recherche (vergers de pistaches Rafsanjan en Iran). L'optimisation du système d'irrigation est un des facteurs les plus importants pour améliorer l'efficience de l'eau dans cette région. Ce projet de recherche visait à comparer l'applicabilité de deux différents types d'irrigation, l'irrigation de surface traditionnelle et un goutte-à-goutte de subsurface relativement bon marché (tuyau percé recouvert de tissu plastique). À cette fin, deux parcelles de 720 m^2 contenant chacune 39 pistachiers ont été sélectionnées dans un verger et les deux parcelles ont été irriguées avec exactement la même quantité et qualité d'eau pendant 3 ans. À la fin de la deuxième année, les parcelles ont été récoltées séparément et comparées. Le rapport du poids de récolte en frais et séchée entre le goutte à goutte de sub-surface et l'irrigation de surface était respectivement de 1.895 et 2 pour la deuxième année, and 2.17 et 2.12 pour la troisième année. Un autre paramètre mesuré pour les arbres de deux parcelles a été la croissance

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annuelle. La valeur de l'indice de croissance en irrigation de surface a été de 2238 cm, là où en goutte à goutte de sub-surface il a été de 4580 cm. En outre, le poids sec de mauvaises herbes en irrigation de surface a été de 82 kg et n'était que de 21 kg en goutte à goutte de sub-surface. Ces résultats témoignent de la différence considérable dans l'efficience des deux systèmes d'irrigation, la préférence allant largement au goutte à goutte de sub-surface par rapport à l'irrigation de surface traditionnelle.

MOTS CLÉS: irrigation de sub-surface; efficience de l'irrigation; vergers de pistaches; efficience de l'utilisation de l'eau; utilisation de l'eau en zone aride; optimisation de l'irrigation

INTRODUCTION

Water is the natural resource on which human life, food security and the health of ecosystems depends. In other words, water resources are one of the main natural resources necessary for life as drinking water, irrigation water and water for industrial uses.

In dryland environments due to high temperature, wind and low humidity there is a specific condition where water shortage is the main limitation on development. Much of the water that is available to people living in dryland regions is found in large rivers that originate in areas of higher elevation. Groundwater resources can also be available to help support development, but relatively limited recharge of groundwater resources is dependent largely on the amount, duration and intensity of rainfall as well as soil properties. However, most of the dryland environments including the area of this research are characterized generally by inadequate and variable rainfall. Rainfall variability and occurrence of prolonged periods of droughts are a characteristic of these areas that must be recognized in the planning and management of natural and agricultural resources.

The research area is typically windy, largely because of the scarcity of vegetation and other obstacles that can reduce air movements. Wind moves the moist air that surrounds plants and soil bodies and as a consequence, decreases atmospheric moisture and increases evaporation rates. Therefore, low precipitation and high evaporation cause inadequate water especially for irrigation. To be able to keep the local pistachio orchards alive and productive, there is no way except operation of efficient methods of irrigation. Subsurface irrigation, especially subsurface drip irrigation (SDI), is one of the new irrigation methods with high efficiency, particularly in arid land environments. It was tested for the first time in California in 1959, and has been developed in other parts of the world. Several investigation projects have been completed on the suitability and applications of SDI in crop production during recent decades. Phene *et al*. (1992) realized that SDI caused an increase in the yield of maize in comparison to other types of irrigation. Hutmacher *et al*. (1992) compared the efficiency of SDI to furrow surface irrigation in alfalfa yield and the result was about 20% more yield and 6% less water use for SDI in comparison to the other types of irrigation. Oron *et al*. (1999) after some investigations reported that water loss control, weed growth control and also better control of the irrigation process are the main advantages of SDI. Camp (1998) evaluated the relevance of SDI for different crops and specified more than 30 types of crops that can derive benefit from SDI. Phene (1995) compared SDI and DI (drip irrigation) for irrigation of tomato, and reported better performance of SDI over DI. Martinez *et al*. (1991) evaluated the effect of fertilizers on growth and as well as the yield of maize using SDI and DI, and reported higher performance of SDI over DI. Zoldoske *et al*. (1995), Solomon and Jorgenson (1993), Camp *et al*. (2000) and Abdi (2003) evaluated the efficiency and suitability of SDI for turfgrass and mentioned several advantages for this type of irrigation.

This research project was designed to compare the applicability of two different types of irrigation: surface irrigation (which is traditionally used by local farmers) and subsurface irrigation using perforated pipe covered with plastic cloth (as a new method in this region).

RESEARCH METHOD AND MATERIALS

Study area status

The study area is a selected part of the pistachio orchards of Tajabad Kohneh in Rafsanjan county, Kerman province of Iran. This area is in fact a dryland region with mean annual precipitation less than 100 mm and potential evapotranspiration over 3000 mm. In this region much of the precipitation is lost by evaporation and as a result groundwater is recharged only locally by seepage through the soil profile. Surface runoff events, soil moisture storage, and groundwater recharge in this region are generally more variable and less reliable. However, groundwater is frequently used at rates that exceed recharge.

In the area of Rafsanjan plain there is no permanent river stream, as well as no considerable reservoir to provide required water. Therefore, groundwater has been the main and only available water source to a relatively rapid growing population during recent decades. However, more discharge and less recharge to the groundwater have led to approximately a 1 m (on average) fall of the water table in some parts of the plain every year. During the last 10 years many productive pistachio orchards have been left without irrigation and abandoned just because of water scarcity. Due to the large fall in the water table occurring over the last few decades, extraction of water is now too expensive in addition to its decreasing quality. The salinity of water increases year on year and its EC is now about 3 mmho cm^{-1}. Therefore, irrigation water quantity and quality limitation are the main problem of agricultural development in the area of this research project (Rafsanjan pistachio orchards). In these conditions, one of the most important priorities could be irrigation system optimization. Systems with high efficiency can help farmers to use available water more efficiently to mitigate the accelerating damage from irrigation water shortage, and get more benefit from a smaller amount of water. In this way, of course, relevant investigations could help and encourage farmers to choose and establish preferred irrigation systems. This research was designed to evaluate the applicability of a traditional irrigation method (surface irrigation) in comparison with a new one (a simple design of subsurface drip irrigation) from different points of view.

Preparation of research plots

For implementation of this research project, two plots, each containing 39 pistachio trees and 720 m^2 in area, were selected in an orchard near Rafsanjan, and isolated (hydrologically) from each other as well as from other parts of the orchard. It should be added that trees in both plots were acceptably similar in terms of age, canopy and stem diameter as well as outward appearance. Then one of the plots was prepared for surface irrigation which is common in the area, and the other one for subsurface irrigation. For the latter, two lines of perforated PVC pipe covered with plastic cloth were located on two sides of the tree line about 1.5–2 m distant from it, and along the whole length of the tree line, at a depth of about 50 cm under the soil surface (Figure 1). Fine sand with thickness of about 10 cm was used as a filter around the pipes to prevent obstruction of the pipe holes (Figure 2).

The new subsurface drip irrigation implemented in this research has some advantages over conventional drip irrigation and subsurface drip irrigation methods. These advantages can be summarized as follows:

- *Simplicity in design and operation*: Plastic cloth is sewn in the shape of long sleeves and then perforated PVC pipes are put through the sleeve-shaped cloths, then it is ready to lay through the channel at about 50 cm depth, and after using the filter which is provided from local sand dunes, the channel is covered by excavated soil;

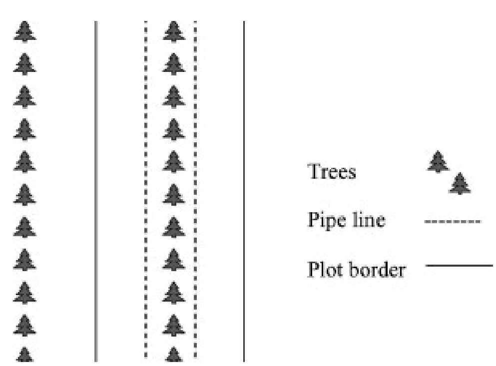

Figure 1. A schematic plan of the irrigation plots and pipeline positions in the subsurface plot

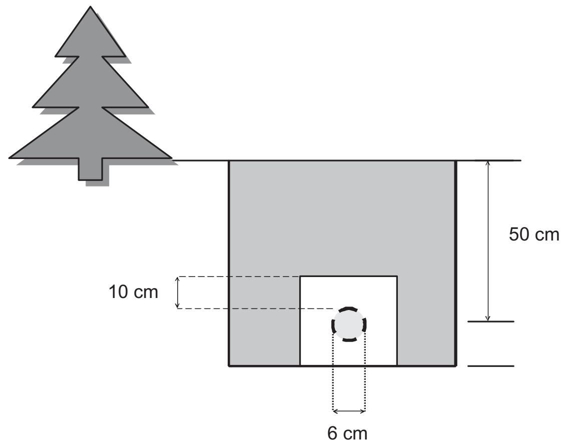

Figure 2. A schematic cross-section of perforated PVC pipe used for subsurface irrigation together with the fine sand filter around it

- *Relatively good durability*: As in this method the pipes are relatively wide (9 cm diameter) and covered with relatively strong plastic cloth and also surrounded by a layer of filter, durability against obstruction and also a uniform exudation of water are almost guaranteed. It needs to be added that in the other part of the orchard where this research project was carried out, exactly the same system had been operated in 1997 and after more than 9 years it was evaluated and tested, and there was no obstruction, blockage or damage to the pipes. It must be mentioned that although it was not implemented as a research project at that time, the purpose was just to keep orchard alive and productive. However, the present research project was started based on this successful experience;
- *Cheapness*: From economical point of view, an initial analysis of the costs for operation and maintenance against benefits from crop increase shows that the money spent will produce a return normally in 4–5 years;
- In this method no boster pump is needed;
- Filtration of water is not required;
- *Compatiblity with the local area water-rights conditions*: most of the farmers in the related region have just 3–4 h of water rights in a period of two weeks, and need a method that can deliver sufficient water to the soil during this short time. This method can fulfil that requirement;
- *Relevance to local ownership*: the area is in a condition of small ownership (farmers own small parts), and it is not economically possible for owners to establish comprehensive and expensive systems for their few hectares of orchard;
- It can be cleaned quite easily by flushing out (at the end of each pipeline there is a outlet that can be opened for this purpose);
- During the winter (when extra water is available) it is possible to have deep surface irrigation for leaching and soil desalinization.

Both plots were irrigated using an exactly equal quantity and quality of water for 3 years. Unfortunately, at the end of the first year we had no crop in the region due to frost. Therefore, comparison of the crop yield was left to the end of the second and third years.

To be able to have a more reliable comparison between irrigation plots, especially the probable effects of irrigation method on soil properties such as EC and pH, soil samples were taken from different depths in both plots before starting the project, at the end of the first year and also at the end of the project. Regular monitoring of soil moisture was also carried out in both plots after irrigation. The rate of crop yield, amount of shoot growth and the quantity of weed growth were the main parameters to be compared in irrigation plots.

RESULTS AND DISCUSSION

At the end of the second year the crop yield in the plots was harvested separately and the weight of fresh as well as dried crop was measured. The weight of the fresh crop in the surface and subsurface irrigation plots was 38 and

Table I. The rate of yield (Pistachio) in surface and subsurface irrigation plots (kg)

	Yield in surface irrigation plot		Yield in subsurface irrigation plot	
	Crop dried weight	Crop fresh weight	Crop dried weight	Crop fresh weight
Second year	21	72	10.5	38
Third year	29	102.9	13.7	47.5

72 kg respectively, and the dried weight in these plots 10.5 and 21 kg respectively. As is seen, the ratio of the weight of fresh and dried crop produced in the subsurface irrigation plot to that of the surface irrigation plot is respectively 1.895 and 2 (Table I). Although production in the third year is higher than the second year, the ratio of crop yield for the third year in the two plots is almost similar to the second year. As is seen in Table I, the weight of the fresh crop in the surface and subsurface irrigation plots was 47.5 and 102.9 kg respectively, and the dried weight in these plots was 13.7 and 29 kg respectively.

In addition to the total weight of harvested crop in each plot, the quality of crop was also compared. To do this the mean weight and size of pistachios were also measured (using a random sample) for crops in both plots. The mean weight of each pistachio produced in the surface irrigation plot was 0.6341 g, whereas it was 0.7082 g in the subsurface irrigation plot. In the other words, the ratio of mean weight as well as dimensions of the pistachios produced in the subsurface irrigation plot to those produced in the surface irrigation plot was about 1.12. Table II shows more details about this measurement.

Another parameter measured for the trees of the two plots was annual shoot growth. This parameter was defined as tree growing index (TGI) as follows:

$$\text{Tree growing index} = \text{TGI} = \sum_{1}^{N} n_i d_i$$

where d_i is the length of the shoot (cm), n_i is the number of shoots with the length of d_i and N is the total number of annual shoots for each tree.

Table III shows the calculation of the growing index for tree number 1 in both plots. In each plot 10 trees were randomly selected and the above index calculated for each one. Then for each plot a plot growing index was calculated as follows:

$$\text{Plot growing index} = \text{PGI} = \sum_{1}^{10} \text{TGI}$$

The value of PGI in the surface irrigation plot was obtained as 2238 cm, whereas in the subsurface irrigation plot it was 4580 cm (Table IV). In fact, the ratio of PGI in the subsurface irrigation plot to PGI in the surface irrigation plot was 2.05. Figure 3 is a graphic comparison of the growing index for the trees in both surface and subsurface irrigation plots.

The last measured parameter was the amount of weed growing in each plot. At the end of the second growing season the dry weight of weed in the surface irrigation plot was 82 kg, whereas it was only 21 kg in the subsurface irrigation plot.

Table II. The mean weight and size of pistachio produced in each irrigation plot

Measured parameter	Surface irrigation plot	Subsurface irrigation plot
Sample weight (g)	312	415
Number of pistachio in sample	492	586
Mean weight of each pistachio	0.6341	0.7082

Table III. Growing index for tree no. 1 in surface and subsurface irrigation plots

Tree no. 1 in surface and subsurface irrigation plots					
Surface irrigation plot			Subsurface irrigation plot		
(1) The length of shoot (cm)	(2) The number of shoots	(3) (1)*(2)	(1) The length of shoot (cm)	(2) The number of shoots	(3) (1)*(2)
0.5	11	5.5	0.5	38	19
1	11	11	1	26	26
1.5	4	6	1.5	6	9
2	5	10	2	8	16
3	3	9	3	6	18
3.5	5	17.5	3.5	2	7
4	1	4	4	6	24
4.5	4	18	4.5	3	13.5
5	2	10	5	2	10
6.5	1	6.5	5.5	2	11
7	2	14	6	3	18
8	1	8	8	1	8
9	1	9	8.5	1	8.5
9.5	1	9.5	11.5	1	11.5
10.5	1	10.5	12	1	12
11.5	1	11.5	12.5	1	12.5
12	2	24	13	1	13
14	2	28	13.5	1	13.5
15	1	15	14.5	1	14.5
16.5	1	16.5	16.5	1	16.5
19	1	19	18	1	18
Tree growing index		262.5	Tree growing index		299.5

Table IV. Total growing index in trees of surface and subsurface irrigation plots

Tree's growing index in surface and subsurface irrigation plots		
Tree no.	Surface irrigation plot	Subsurface irrigation plot
1	262.5	299.5
2	139	945.5
3	262.5	550.5
4	280.5	299.5
5	281.5	252.5
6	196	322
7	201.5	639.5
8	142	357
9	91.5	343
10	380.5	571.5
Plot growth index (tree's index summation)	2,237.5	4,580.5

The results of laboratory analysis of the soil samples taken from various depths in each plot at the beginning and end of the research period show no considerable change in pH and EC of the soil during the study (Table V). As Table V shows, EC had increased slightly in both plots and especially at lower depth during the research period. However, this can be quite normal as both plots were irrigated using saline water ($EC = 3.5\ mmho\ cm^{-1}$).

According to the results taken from this research, the difference in efficiency of the two irrigation systems is considerable for the pistachio orchards in Rafsanjan area. In this area where the irrigation water shortage is the main

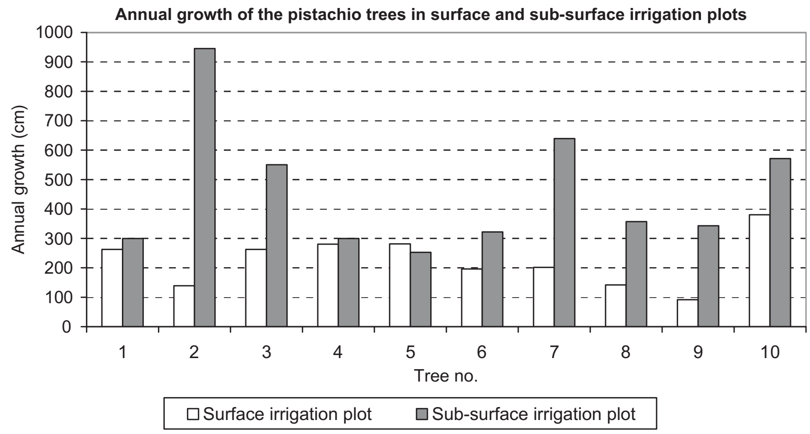

Figure 3. Graphic comparison of annual growth in tree samples from both surface and subsurface irrigation plots

issue, the surface irrigation system which is traditionally used by farmers is not an efficient method as the main part of the irrigation water is lost from the soil surface and topsoil profile due to high evaporation during the year. It must be added that in regional common surface irrigation a considerable proportion of the water is also lost through channels and waterways from source (pump) to the orchards because of deep percolation and evaporation, which has not been considered here. In other words, the amount of water lost from channels and water sources in this irrigation system is in fact in addition to what was considered in this research, as water was taken by tank directly to the plots. However, as for the water applied to the plots it can be said that in the surface irrigation plot a small part is consumed beneficially by the crop, and the larger remaining part is wasted. A considerable portion of the second part evaporates from the plot during irrigation as well as from the moist topsoil during the days after irrigation. As the soil has a fine texture, capillarity is a quite active process even for a relatively long period of time after irrigation. This process brings up the soil water and consequently keeps the process of evaporation active. The third part of the applied water is consumed by the weeds grown in the plot, and then evapotranspired unproductively. Due to the considerable difference between the weights of weed grown in the two plots, the rate of water consumed by weeds

Table V. The results of laboratory analysis of the soil samples taken from both plots at various depths at the beginning and end of the research period

Time of sampling	Factor	Depth (cm)	Surface irrigation plot	Subsurface irrigation plot
Beginning of the research	PH	0–30	7.59	7.80
	EC		5.81	5.34
	Texture		S.L.	S.L.
	EC	30–60	12.28	12.61
	TexturePH		L.7.69	L.7.97
	PH	60–90	7.70	7.89
	EC		22.2	20.3
	Texture		L.	L.
End of the research	PH	0–30	7.64	7.60
	EC		8.78	6.1
	Texture		S. L.	S.L.
	EC	30–60	16.34	14.89
	TexturePH		L.7.55	L.7.58
	PH	60–90	7.66	7.65
	EC		22.3	21.5
	Texture		L.	L.

Table VI. Soil-saturated percentage measured on days after irrigation (in both plots)

Day after irrigation	Saturation percentage							
	Surface irrigation plot				Subsurface irrigation plot			
	20 cm	40 cm	60 cm	80 cm	20 cm	40 cm	60 cm	80 cm
1	43	37.6	33.37	28.67	9.03	42.065	45.59	38.07
2	34.4	42.3	35.25	28.2	9.89	41.83	43.71	39.01
3	30.53	39.95	36.19	27.95	9.46	40.89	42.77	39.95
4	26.66	36.19	34.78	28.2	9.46	39.01	42.3	39.48
5	22.36	34.31	33.37	28.67	9.03	37.13	41.36	38.775
6	19.78	31.49	31.02	28.435	8.6	34.31	40.42	37.13
7	16.34	29.61	29.61	28.67	9.03	31.96	39.245	34.78
8	14.19	26.79	29.14	28.2	8.6	31.02	38.305	34.075
9	13.76	25.85	28.67	28.23	8.6	29.845	36.19	32.43
10	13.33	23.97	27.73	28.26	8.6	28.905	35.25	31.96
11	12.47	22.56	27.26	28.21	8.6	27.73	33.84	31.49
12	12.04	22.09	26.79	28.34	8.6	27.26	33.135	31.208
13	11.18	21.15	26.32	28.37	8.6	27.025	31.96	31.067
14	11.18	20.21	25.85	28.2	8.6	26.978	31.49	30.926

in the surface irrigation plot cannot be ignored. However, the portion of water returning to the aquifer cannot be considerable. This statement is based on data collected from moisture monitoring carried out at different depths from the soil surface in both plots during this research. Table VI shows the soil moisture data measured for a period of time after irrigation in both plots. Variation of the saturation percentage during the days after irrigation is also shown graphically in Figures 4 and 5 for the surface and subsurface irrigation plots respectively.

Groundwater retreat in this area, and the serious water limitation for pistachio orchards (which almost is the only crop for local farmers), necessitate optimization of irrigation systems towards new systems with minimum water loss such as the new subsurface irrigation tested in this research. However, the point that must be made here is the probable impact of crop increase (using the new method) on increased demand for water. This can firstly increase the price of water rights in the region and secondly encourages farmers to extract more groundwater and puts pressure on the aquifer that leads a more negative balance of water resources. It is of course the duty of the local water authorities to control the rate of extraction and also supervise farmers so there is a sustainable water resource beside more crop production and a reasonable level of income.

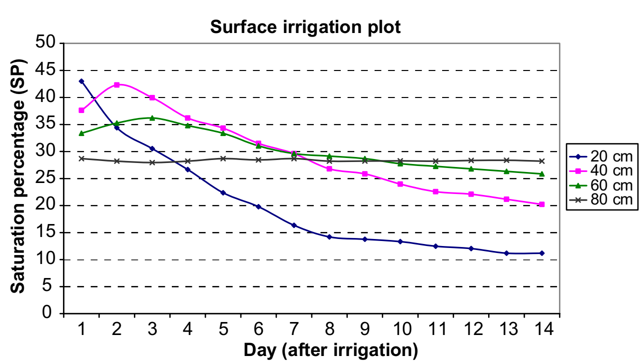

Figure 4. Variation of the saturation percentage during the days after irrigation in the surface irrigation plot. This figure is available in colour online at www.interscience.wiley.com/journal/ird

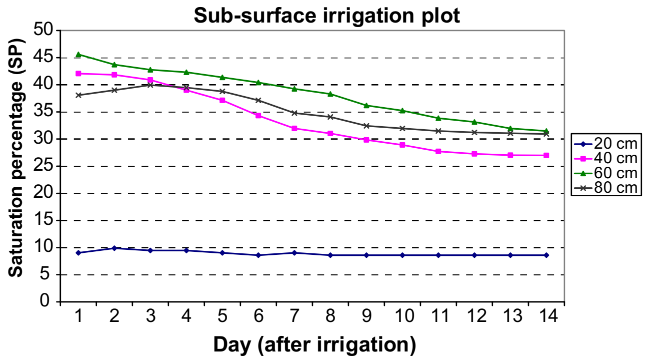

Figure 5. Variation of the saturation percentage during the days after irrigation in the subsurface irrigation plot. This figure is available in colour online at www.interscience.wiley.com/journal/ird

CONCLUSIONS

As mentioned earlier, the amount of crop yield as well as annual shoot growth in the subsurface irrigation plot was about twice as much as in the surface irrigation plot. In addition, the weight of weeds growing in the subsurface irrigation plot was about one-quarter of the weed weight in the surface irrigation plot. Therefore, the difference in water use efficiency of the two irrigation methods is significant for the pistachio orchards in the research area. As the main issue of the area is irrigation water shortage, the surface irrigation system which is traditionally used by farmers has not been an efficient and beneficial method for a long time as a considerable part of water is lost in this method. Groundwater retreat in the area, and the serious water scarcity for pistachio orchards, necessitate optimization of irrigation systems towards new methods with minimum water loss such as the subsurface method tested. This optimization has some cost for farmers, but due to the considerable differences in efficiency of the two irrigation methods and a significant increase of the crop yield in subsurface irrigation, the money spent would be recouped in a reasonable period of time.

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