Evaluation of the Effects of Alternate Furrow Irrigation on Yield and Water Use Efficiency of Potato

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Abstract

The objective of water management is to provide suitable moisture environment to crop to obtain maximum yield with high water use efficiency. The increasing world wide shortage of water resources requires the optimization of irrigation management in order to improve water use efficiency. This paper evaluates the effect of partial root zone drying (PRD) on potato yield and water use efficiency by method of alternate furrow irrigation. The analyses was based on Agronomic parameters and soil moisture content data collected during two years field work at a place near Adet Agricultural Research Center for two years period (i.e. January -June 2007 and 2008). The analysis was performed using statistical software, MSTATC. Appropriate standard errors of the means (SE) and least significant differences (LSD_s) at P = 0.05 were calculated. The response of each agronomic parameter to three water levels and three furrow water application methods, and the relative moisture status under each treatment has been evaluated. Tremendous water saving was made possible in this experiment. Up to 42% water saving was practically achieved with 82% and 45% improvement in WUE in CFI and AFI methods respectively. Water saving to this extent has practically significant meaning on the overall water management system. It was found that as compared to the control (i.e. CFI with 100% IR level which is assumed to represent farmers practice), PRD treated potato under half (50%) IR level resulted only in 15% marketable yield reduction.

Key words: Alternate Furrow, Irrigation, Partial Root Zone Drying, Water `Use Efficiency, Irrigation Requirement

Introduction

The success of irrigation in ensuring food security and rural welfare has been impressive, but past experiences also indicate that inappropriate management of irrigation has contributed to environmental problems including excessive water depletion, water quality reduction, water logging and salinization (Mark et al., 2002).

Many countries depend on surface irrigation to grow crops for food and fiber. Without surface irrigation their agricultural production would be drastically lower and problems of unreliable food supply, insufficient rural income and unemployment would be widespread. Although precise data are lacking, estimation of surface irrigation accounts for some 80 to 90 percent of the total 7260 million hectares of irrigated land worldwide, mainly in developing countries in the tropics and sub-tropics, where hundreds of millions of farmers depend on surface irrigation to grow their crops (Yesuf, 2004).

FAO (1989) indicated the problems irrigated agriculture may have to face in the future. One of the major concerns is the generally poor efficiency with which water resources have been used for irrigation. A relatively safe estimate is that about 40 percent or more of the water diverted for irrigation is wasted at the farm level through either deep percolation or surface runoff.

Water is one of the largest renewable natural resources but fresh water is expected to emerge as a key constraint to future agricultural growth. Globally, and more particularly in developing countries, changing water availability and quality pose complex problem and management options are not easy. The changing situation comes partly from increasing demands such as population, industry and domestic requirements and partly from consequences of climatic change (Magar, 2006). Therefore, great emphasis is placed in the area of *crop physiology and crop management* with the aim to make plants more efficient in water use under dry condition (Stikic et al., 2003).

Poor management of agricultural water leaves almost all parts of Ethiopia highly susceptible to rainfall variability which depicts itself in terms of prolonged dry spell and drought (Seleshi, 2006). Over 70% of the country is either arid or semi arid, characterized by low and erratic rainfall both in terms of spatial and temporal distribution (Kamara, 2002). This is one of the most challenging problems that limit agricultural production, and makes larger parts of the country vulnerable to recurrent drought.

Therefore, it is necessary to consider the on farm design and management factors that improve the water use efficiency by choosing appropriate method of irrigation water application. The overall objective of this paper is to evaluate the effect of partial root zone drying by a technique of alternate furrow irrigation on yield and water use efficiency of potato.

The concept of partial root zone drying

Partial root zone drying (PRD) is a practice of using irrigation to alternately wet and dry (at least) two spatially prescribed parts of the plant root system to *simultaneously maintain plant water status at maximum water potential* and *control vegetative growth* for prescribed parts of seasonal cycle of plant development. The reason for doing this is to control vegetative growth or improve water use efficiency or both while maintaining reproductive growth & development.

If part of the root system was allowed to dry and the remaining roots were kept well watered, chemical signals produced in the drying roots reduced stomata aperture. At the same time the fully hydrated roots maintain a favorable water status through out the aerial parts of the plant. In addition to reduced stomatal conductance, it was noted that shoot extension was also inhibited as a result of partial root drying. A surprising finding was that the effect was *temporary*, and despite the fact that part of the root system remained dry, stomatal conductance, photosynthesis and growth returned to pre-treatment levels within a few weeks (Kriedemann et al., 2003).

Abscisic acid and cytokinins are plant hormones. Plant hormones can act as chemical signals (Stoll, 2000). ABA is an effective stomatal closing agent and relationship between stomatal conductance and xylem (ABA) generated from data collected in field suggest that ABA can have controlling influence and determine day to day variation in stomatal behavior as soil dries as well as leaf to leaf variation in conductance when different cultural treatments are applied. ABA induced partial stomatal closure and reduced leaf area have been considered to be the main causes for saving water in plants under PRD treatment (Davis et al. 2002).

It was also found that PRD caused a reduction in the levels of other plant hormones called *cytokinins*. The function of these is to stimulate transpiration and to control the development of side shoots in the canopy. The combined effect of these hormonal changes was to reduce water losses and also to reduce the total size of the leaf canopy. Armed with knowledge about the transient nature of the effect and the likely role of the chemical signals it is possible to devise irrigation schedule which keep one part of the root system , or other in a state of drying so as to maximize the production of chemical signals and hence their inhibitory effect on transpiration and growth. (Kriedemann et al., 2003)

Materials and methods

The field experiment was conducted near Adet ($11^0$17'N, $37^0$43'E). It is about 490 km NW of Addis Ababa and 43 km from the capital of the Amhara National Regional State (Bahir Dar). It has an altitude of 2240 m.a.s.l. and represents mid to high altitudes and high potential areas (ANRSBOA, 1999). Mean daily maximum temperature ranges from 22.5^0C (July and August) to 29.4 ^{0}C (March) and the mean daily minimum temperature ranges from 5.4 ^{0}C (January) to 12.1 ^{0}C in August. Mean annual rain fall in the area is about 1238.7 mm. Soils in the study area are moderately acidic (pH=5.41) and are moderate in its organic matter content (i.e. 2.17%). The relative proportion of sand, silt and clay (15%, 27% and 58% respectively) revealed that the soil of the testing site is clay in its very nature.

In this experiment three furrow irrigation water application methods were tested. These include:

1. Conventional furrow irrigation (CFI), where every furrow is irrigated during each watering.
2. Fixed furrow irrigation (FFI), where irrigation is fixed to one of the two neighboring furrows throughout the growing period and
3. Alternating furrow irrigation (AFI) where one of the two neighboring furrows is alternately irrigated.

Each of them was tested on three separate plots. Each irrigation method was again further divided into three treatments using different levels of irrigation requirements: i.e. full (100%), 75%, and 50% irrigation requirement levels during each watering.

Moreover, each treatment was replicated three times and a total of 27 plots each with an area of 18m^2 (3m x 6m) were used. Four furrows were arranged on each plot. The spacing between two furrows was 75cm. The length of each furrow was limited to 6m. The spacing between plants is 30cm and between rows of plants 75 cm was provided. The spacing between treatments was kept 1m and the spacing between each block was 2m. Totally, the experiment comprises of three blocks. Each block contains nine randomly arranged treatment sets. The total land required for this experiment was about 0.1014 ha (26m x 39m).

The parameter set up and treatment combinations are as follows:

Factor 2 (Irrigation requirement levels)		Factor 1 (Water application methods)		
	100 %	CFI	FFI	AFI
	75%	CFI	FFI	AFI
	50%	CFI	FFI	AFI

Ten years data of on maximum and minimum temperature, relative humidity, wind speed, sunshine hours and rainfall from the nearby station was collected from National Meteorological Authority. The crop water requirement and irrigation requirement of potato was estimated using CropWat 4 Windows Version 4.3 (FAO, 1989). Running this model with the aforementioned and other input data, the crop water requirement and irrigation requirement of potato at the study area was estimated.

Accordingly, the crop water requirement and irrigation requirement of potato at the study area was found to be 522mm and 430mm respectively. As a result, for each watering the full (100%) irrigation requirement level was found to be 22mm. Depending on this value, the 75% irrigation requirement level and 50% level was fixed as 16mm and 11mm respectively.

After the land preparation work, the early maturing potato variety (locally called 'Wochecha') was selected for planting. Potato seeds were allowed to properly sprout and then planting was done. Plant density for each treatment was 80 seeds per $18m^2$ plot. To facilitate proper establishment of the crops, each treatment was supplied with full (100%) irrigation for two consecutive weeks before the actual treatment commenced.

Weeding and other agronomic practices were conducted on time equally for each treatment. Irrigation water was then supplied from the farm channel into the field through siphons for every treatment. Soil samples were taken for analysis of soil texture, bulk density, pH and organic matter content and soil moisture content. The analysis was made using standard procedures. The moisture content is determined using gravimetric method. To determine the agronomic parameters such as plant height, stem diameter, yield, total biomass, root dry weight, shoot dry weight and root to shoot ratio, generally 10 plants were sampled at random and marked from central two rows from each plot.

The data collected for all relevant variables were subject to analysis of variance appropriate to factorial experiment RCBD (Gomez & Gomez, 1984). Appropriate standard errors of the means (SE) and least significant difference (LSD_s) between and / or among treatments at P = 0.01 and P = 0.05 were calculated using the MSTATC computer program.

Results and discussion

Soil moisture analysis

This section presents the results of soil moisture content analysis for soil samples taken from each plo

Figure 1. Moisture content at 30 cm depth both at drying and wetting side of the furrow before irrigation. (FFI-22, FFI-16, FFI-11: fixed furrow irrigation at 22mm, 16mm and 11mm water application depths respectively. AFI-22, AFI-16, AFI-11: alternate furrow irrigation at 22 mm, 16mm and 11mm water application depths respectively. 30cm-W: 30cm depth and wetting side, 30cm-D: 30cm drying side).

Moisture content in the wetting side exceeds that of the drying side, both before and after irrigation. This clearly justifies the existence of moisture gradient between the two sides of t

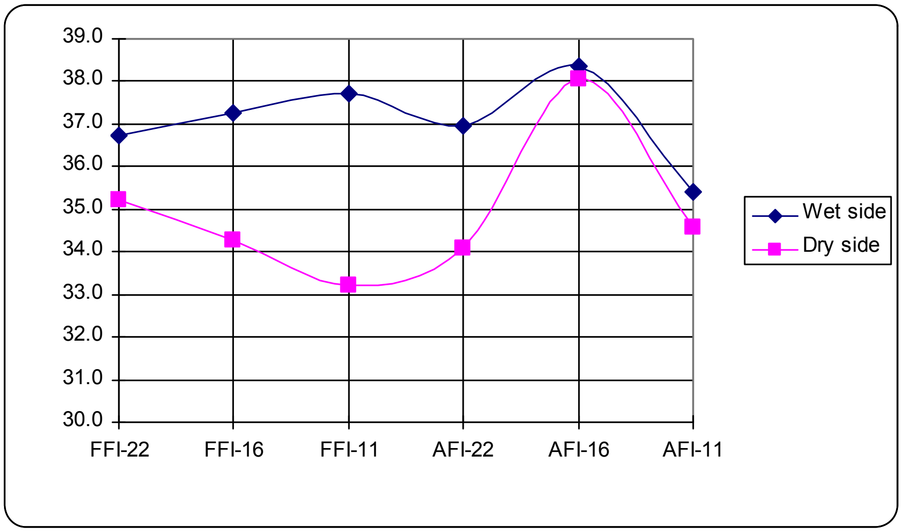

Figure 2 Moisture content at 60 cm depth both at drying and wetting side of the furrow before irrigation

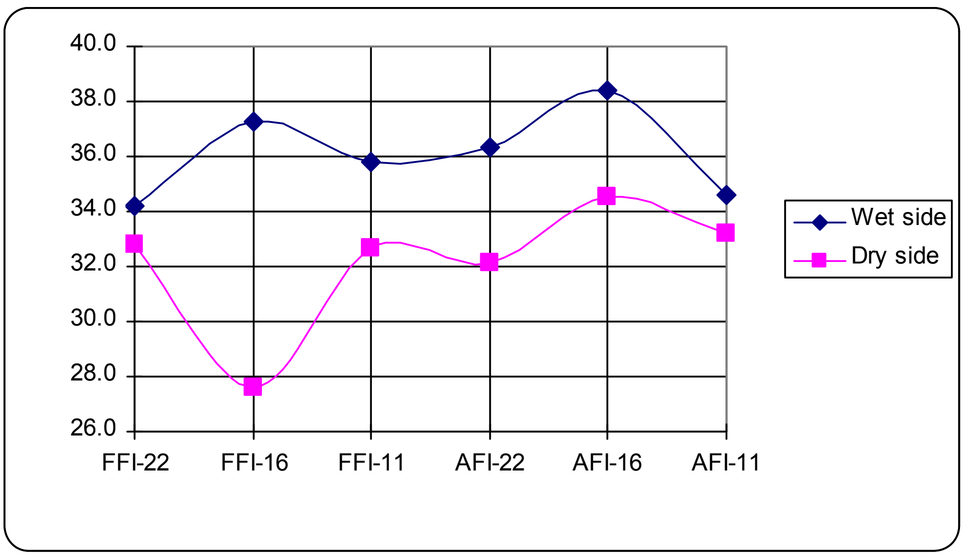

Figure 3 Moisture content at 30 cm depth both at drying and wetting side of the furrow after irrigation

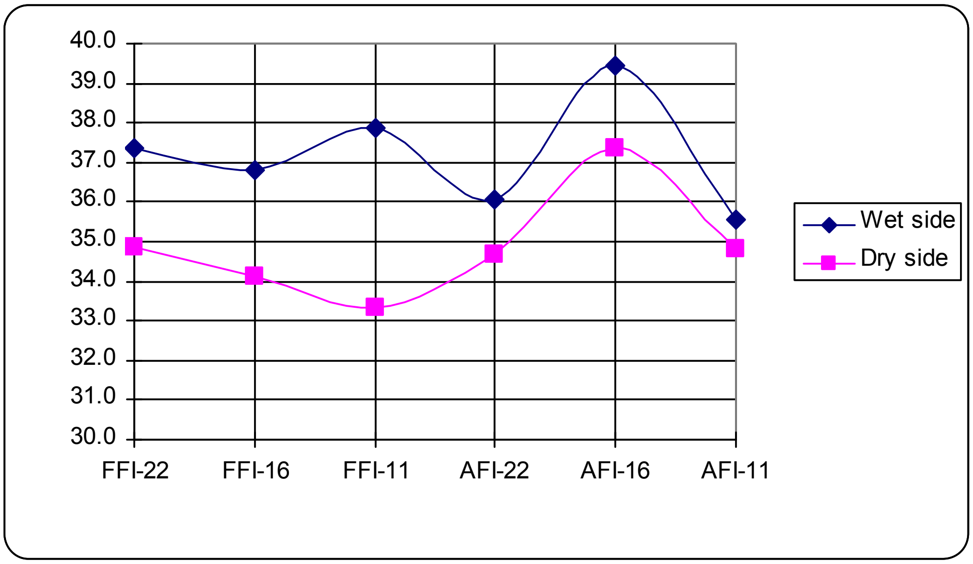

Figure 4 Moisture content at 60 cm depth both at drying and wetting side of the furrow after irrigation

Plant growth and yield parameters

The combined Statistical analysis of most agronomic parameters of the two years (2007 and 2008) data using MSTATC revealed that water application method and / or irrigation water application level resulted into non-significant difference in each treatment. Application of 75% IR level of water under fixed furrow irrigation (FFI-75%) resulted in larger plant height (25.38cm) than the conventional furrow irrigation (23.27cm) under the same water application level (Tab. 1). As the water level declines, the potato crop tends to manage the deficit by controlling its vegetative growth (physiological development) in AFI.

Table1 also shows no statistically significant difference in stem diameter among treatments. This result signifies that there was no injurious water deficit in the shoot at its growing stage when the stem diameter was measured. This also means plant water status was maintained at maximum water potential.

In addition, total biomass was not significantly affected by water application depth and / or IR level (Table 1). This suggests absence of injurious water deficit during the growing period in each treatment. This result goes in line with the fact that AFI tends to manage moisture deficit by controlling vegetative (physiological development) of the crop. Fresh root weight value with AFI at 50% IR level (9.93qt/ha) was higher than CFI values at all IR

Table 1 Comparison of Agronomic Parameters

Treatments	Plant height (cm)	Stem dia. (mm)	No of tubers /plant	Tuber weight (gm)	Total biomass qt/ha	Fresh root weight qt/ha	Dry root weight qt/ha	Fresh shoot weight qt/ha	Dry shoot weight qt/ha	Root /shoot ratio
CFI-100%	23.35	10.02	7.85	71.44	214.43	8.48	2.75	75.12	11.23	0.229
CFI-75%	23.27	9.94	8.57	69.55	239.06	9.71	2.8	89.53	12.43	0.215
CFI-50%	23.62	9.83	8.19	64.65	232.01	8.57	2.67	78.73	10.87	0.222
FFI-100%	24.04	9.96	9.28	66.95	237.07	9.94	2.86	82.83	12.64	0.21
FFI-75%	25.38	10.12	8.47	70.31	251.31	9.15	2.97	87.10	11.85	0.237
FFI-50%	20.98	10.29	6.86	63.88	173.86	5.86	1.99	63.74	9.83	0.208
AFI-100%	24.00	9.79	8.05	64.22	214.68	8.56	2.60	75.00	12.65	0.194
AFI-75%	24.73	10.20	7.47	58.13	174.39	8.28	2.30	71.10	11.00	0.19
AFI-50%	23.73	9.78	7.63	57.27	196.63	9.93	2.88	71.69	10.92	0.234
LCD(0.05)	ns	n	ns	ns	ns	ns	ns	ns	ns	ns
CV(%)	7.84	7.87	16.16	17.94	20.87	22.31	24.45	27.11	19.24	21.05

NS: non-significant difference at 5% probability level, CFI: conventional furrow irrigation, FFI: fixed furrow irrigation, AFI: alternate furrow irrigation, (100%, 75% and 50% are irrigation requirement levels) CV (%): Coefficient of variation in percent, LSD (5%): least square difference at 5%

Table 2 Comparison of yield and biomass performances

Treatments	Total Yield qt/ha	Marketable Yield qt/ha	Non-Marketable Yield qt/ha	Dry Matter Content %
CFI-100%	131.59	118.6	13.05	24.38
CFI-75%	145.05	131.12	14.07	22.92
CFI-50%	140.23	125.87	14.01	24.59
FFI-100%	144.05	128.21	15.72	25.04
FFI-75%	147.41	130.78	16.61	23.76
FFI-50%	100.45	88.5	12.42	24.76
AFI-100%	122.53	115.2	17.46	23.34
AFI-75%	104.21	84.29	19.53	23.61
AFI-50%	114.64	100.37	14.3	27.05
LCD(0.05)	ns	Ns	ns	ns
CV(%)	21.21	19.64	49.78	15.92

NS: non-significant difference at 5% probability level, CFI: conventional furrow irrigation, FFI: fixed furrow irrigation, AFI: alternate furrow irrigation, (100%, 75% and 50% are irrigation requirement levels), CV (%): Coefficient of variation in percent, LSD (5%): least square difference at 5% levels. This indicates better root development in AFI than CFI treated plots. The highest value for dry root weight (2.88qt/ha) is obtained with AFI at 50% IR level, followed by FFI at 100% IR level. The maximum root to shoot ratio (0.237) was obtained from FFI at 75% level followed by (0.234) for AFI at 50% level. This indicates existence of better root development than shoot unlike CFI at the same level. This also means presence of better root density in AFI than CFI at 50% IR level.

AFI at 50% IR level brought the highest dry matter content (27.05%) as compared to the other treatments. This goes in with the fact that PRD maintains quality.The highest total yield (147.41 qt/ha) was obtained with FFI at 75% level followed by (145.05 qt/ha) resulting from CFI same irrigation requirement level. CFI showed an improvement (from 131.59 qt/ha to 140.23 qt/ha) in total yield as the IR level declines from 100% to 50%. Total yield of AFI at 50% level (114.64qt/ha) showed only 13% yield decline when compared with CFI at 100% IR level (131.5 qt/ha). This originates probably from the very nature of AFI in maintaining yield at lower water level. Very interesting result was that better value of marketable yield was obtained at 75% (131.12 qt/ha) and 50% level (125.27 qt/ha) than the 100% IR level in CFI. AFI at 50% IR level brought 100.37 qt/ha marketable yield, which is lower than the value obtained by CFI at 100% IR level by only 18.23 qt/ha (i.e. 15.4%). At 50% IR level, AFI method gave better marketable yield than FFI method. This justifies the fact that alternating irrigation on both sides of the furrow maintains quality of potato than fixing irrigation to one side at lower water level.

Water Use Efficiency

As can be seen from table-3, WUE showed progressive improvement in CFI treated plots as the IR level decreases from 100% to 75% and then to50%. The highest value for WUE (8.13kg/m3) was obtained at 50% IR level for CFI followed by AFI at the same level. When CFI and AFI are compared at the same water level, CFI resulted into a better WUE

Table 3 Comparison of the Water Use Efficiency

	Irrigation requirement level (%)	Marketable yield (qt/ha)	Volume of water applied (m^3/ha)	Water use efficiency (kg/m^{3})
CFI	100	118.6	2640	4.49
	75	131.12	2040	6.43
	50	125.87	1540	8.17
FFI	100	128.21	2640	4.86
	75	130.78	2040	6.41
	50	88.5	1540	5.75
AFI	100	115.2	2640	4.36
	75	84.29	2040	4.13
	50	100.37	1540	6.52

than AFI. In general, WUE can be increased by 82% in CFI and by 47% in AFI by reducing the IR from 100% to 50% level. When CFI at 100% IR level (which assumed to be close to the farmers practice) is compared with AFI at 50% IR level, WUE improves from 4.49 kg/ m3 to 6.52 kg/m3 which is about 45% improvement. Here marketable yield declines from 118.6 qt/ha to 100.4 qt/ha which is only 15% reduction. Water consumption by the crop is also reduced to 58% by adopting this method.

Conclusions and Recommendations

Different suggestions by various scholars were cited about the working principles of PRD. The first line of thought has two theoretical back grounds. (i) Fully irrigated plants usually have widely opened stomata. A small narrowing of the stomatal opening may reduce water loss substantially with little effect on photosynthesis. (ii) Part of the root system in drying soil can respond to the drying by sending a root-sourced signal to the shoot where stomata may be inhibited so that water loss is reduced. Here manipulating the soil water conditions using PRD, there by altering chemical signals, is thought to manipulate stomatal conductance (Stoll, 2000).

The other dimension of thinking by the second group of scholars is that stomatal control only constitutes part of the total transpiration resistance. The boundary resistance from the leaf surface to the outside of the canopy may be so substantial that reduction in stomatal conductance is small and may be partially compensated by the increase in leaf temperature(Kang and Zhang,2004).

In addition, PRD can expose part of the root system to soil drying and the roots in the drying zone may produce a signal that restrict stomatal opening. Although this might be expected to increase the WUE as outlined above, the situation is complicated by the fact that, in many crop canopies, the stomatal control over transpiration is only minimal and depends on the degree of environmental or atmospheric coupling (Jarvis, 1981, 1985; Jarvis and Mc Naughton, 1986). Canopy transpiration will largely be determined by huge boundary resistance and the energy input that sets the leaf temperature difference. If the stomata are partially closed, the leaf will be heated up, the vapor gradient will be higher, and the transpiration will eventually reach an equilibrium rate where the energy input matches the energy used by evaporation.

As it was indicated in the previous sections, the response of most agronomic parameters such as plant height, stem diameter, number of tubers per plant, tuber weight, dry matter content, total biomass, total yield, number of plants per plot, root and shoot weight to water application method and/ or IR level was found to be statistically non-significant. This suggests that introducing PRD even at 75% and 50% IR level had no injurious effect on the growth of potato crop. During field observation also it was seen that PRD treated plots showed no vigorous variation with that of the fully irrigated control treatments physiologically. Moreover, there was no major variation in days required to reach maturity.

Tremendous water saving was made possible in this experiment. Up to 42% water saving was practically achieved with 82% and 45% improvement in WUE in CFI and AFI methods respectively. Water saving to this extent has practically significant meaning on the overall water management system. It minimizes the risks associated with water logging, evapotranspiration and deep percolation loss, leaching of minerals and salt buildup in the system which may result due to excess water application. Moreover, the 42% water which is saved could be used for other beneficial purposes: i.e. to extend irrigable area or to irrigate high value crop or provide supplementary irrigation for rain fed crops. Reduction in pumping cost, labor and time are additional benefits.

As compared to the control (i.e. CFI with 100% IR level which is assumed to represent farmers practice), PRD treated potato under half (50%) IR level resulted only in 15% marketable yield reduction. PRD can be seen as a more efficient irrigation strategy where a small amount of water is available particularly as it doesn't result in significant yield penalties (Stoll, 2000). A slight decrease in yield as a response to halving the amount of irrigation water may be acceptable if fruit quality improves. Compared to other deficit irrigation techniques the yield reduction measured under PRD condition relative to control was minor (Stoll, 2000 and Dry, 1997) A consistent feature of these trials was that there was no significant reduction in yield due to PRD treatment, even though the amount of irrigation was halved. Accordingly, in this experiment, the maximum dry matter content (27%) was obtained with 50% (half level) irrigated PRD treated potato crop which is an indicator of better quality. The WUE improved by 45% as compared to the control. Most recently, a study by Saeed et al. (2005) showed also that PRD could also modify shoot growth and increase WUE in potatoes. However, the physiological basis for improving WUE in potatoes under PRD remains unknown. Moreover, AFI has certain advantages over CFI. It requires less labor during water application, less irrigation time and it has lesser chance for evaporation since lesser surface area is exposed to the environment.

The relatively low performance of FFI at lower (50% IR level) could be associated with the prolonged exposure of roots to drying. It is thought that this condition may cause exposure of roots to drying soil and may bring anatomical changes in the roots such as, suberization of the epidermis, collapse of the cortex and loss of succulent secondary roots (North and Noble, 1991). These changes are such that the roots under prolonged soil drying may function simply as transportation 'pipes' with a very low radial permeability of water. Such hydraulically isolated roots in soil would have reduced ability to sense soil drying. On the contrary, alternate watering or re watering, after long period of soil drying, may improve this situation by inducing new secondary roots (Liang et al., 1996b).

Therefore, CFI and AFI at 50% IR level can help efficient utilization of water with insignificant or no yield loss especially in areas where irrigation water is scarce and in water harvesting schemes to make crop production possible with limited water. Moreover, to maximize the utilization of the existing potentials of PRD, further research on broader range and variety of horticultural crops at different location is still required.

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