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Potato Yield and Quality Response to Deficit Irrigation

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Abstract. **Four potato (*Solanum tuberosum* L.) varieties were grown under four season-long sprinkler irrigation treatments in three successive years (1992–94) on silt loam soil in eastern Oregon. The check treatment was irrigated when soil water potential (SWP) at the 0.2-m depth reached –60 $J \cdot kg^{-1}$ and received at most the accumulated evapotranspiration (Et_c) to avoid exceeding the water-holding capacity of the top 0.3 m of soil. The three deficit irrigation treatments were irrigated when SWP at the 0.2-m depth reached –80 $J \cdot kg^{-1}$ and had the following percent of the accumulated Et_c applied at each irrigation: 1) 100%, 2) 70%, and 3) 70% during tuber bulking with 50% thereafter. Based on regression of applied water over 3 years, potatoes lost both total and U.S. No. 1 yields when irrigations were reduced. Based on regression on applied water, when irrigation was reduced gross revenues declined more than production costs, resulting in a reduction in profits. Leaching potential, as determined by the SWP treatments, was low for all treatments. The results of the study suggest that deficit irrigation of potatoes in the Treasure Valley of Oregon would not be a viable management tool, because the small financial benefits would not offset the high risks of reduced yields and profits from the reduced water applications.**

Agriculture in the Pacific Northwest is coming under increased political pressure to reallocate water from irrigation to instream flows for preserving fish stocks, providing for water and power needs of growing urban areas, and reducing non-point source pollution of groundwater and surface water. Deficit irrigation may be one approach to address these issues. Deficit irrigation is a strategy that seeks to optimize economic efficiency (English et al., 1990). Crops are allowed to sustain some degree of water deficit in order to reduce irrigation costs and potentially increase revenues. If the reductions in revenue due to the reduced yields are less than the reductions in irrigation costs, then deficit irrigation can, in principle, lead to increased profits when water costs are high or when water supplies are limited (English, 1990).

Deficit irrigation has been used successfully with a number of crops (English et al., 1990). Deficit irrigation of potatoes, however, could be difficult to manage because reductions in tuber yield and quality can result from even brief periods of water stress (Eldredge et al., 1992, 1996; Lynch et al., 1995; Shock et al., 1992, 1993; Wright and Stark, 1990). Previous studies have demonstrated that potatoes can tolerate deficit irrigation before tuber set without significant reductions in tuber external and internal quality (Cappaert et al., 1994; Shock et al., 1992). The Russet Burbank cultivar is predominant in the Pacific Northwest; however, in this cultivar short duration shortages in water supply during early tuber bulking induce losses in tuber grade and internal quality directly related to market value (Eldredge et al., 1992, 1996). Potato cultivars differ in their tolerance to water stress (Jefferies and MacKerron, 1993a, 1993b; Lynch and Tai, 1989; Lynch et al., 1995; Martin and Miller, 1983; Miller and Martin, 1987a, 1987b; Shock et al., 1993). The adoption of new potato cultivars by growers and processors makes it desirable to reexamine deficit irrigation.

The advent of more efficient irrigation methods allied with the use of soil moisture monitoring devices can make deficit irrigation of potatoes more manageable. Sprinkler irrigation allows more precise control of the amount of water applied than furrow irrigation, allowing more accurate management of crop root zone soil moisture. Irrigation scheduling with a target soil water potential (SWP) level can provide the feedback for managing sprinkler irrigations. Optimum potato yield and quality have been achieved by maintaining the soil water potential in the top 0.3 m of silt loam soils wetter than –60 $J \cdot kg^{-1}$ (Eldredge et al., 1992, 1996; Holder and Cary, 1984; Shock et al., 1992; van Loon, 1981). Water applications at each irrigation can then be adjusted to avoid saturated flow below the top 0.3 m of soil.

The objectives of this research were to 1) determine potato response to mild, season-long precision deficit irrigation by partial Et_c replacement at SWP of –80 $J \cdot kg^{-1}$; 2) compare the responses of major commercial varieties to deficit irrigation; and 3) evaluate the potential for deficit irrigation to improve economic efficiency of potato production.

Materials and Methods

The trials were conducted in three successive years on an Owyhee silt loam (coarse-silty, mixed, mesic, Xerollic Camborthid) at the Malheur Experiment Station, Oregon State Univ. in Ontario, Ore. Potatoes followed alfalfa in 1992, and spring wheat in 1993 and 1994. Fields were bedded into 0.9-m-wide hills in the fall of each year. Tuber seed pieces (60 g) were planted in late April at 0.23-m spacing. Residual soil nitrate-N plus ammonium-N in the upper 0.3 m in late March was 62, 45, and 30 $kg \cdot ha^{-1}$ in 1992, 1993, and 1994, respectively. Nitrogen fertilizer at 22, 174, and 134 $kg \cdot ha^{-1}$ in 1992, 1993, and 1994, respectively, was applied uniformly to all plots. Because of adequate residual soil N following alfalfa in 1992, the N fertilizer was applied as a single postemergence application; in 1993 and 1994, it was applied as a combination of preemergence and postemergence applications. Preemergence applications were made within one week after planting by banding urea in both sides of the potato hill at the same level as the seed piece and offset 0.23 m to the side. Nitrogen fertilizer for postemergence applications was applied to the plots as broadcast urea immediately before an irrigation or as urea-ammonium nitrate solution injected through the sprinkler system.

In the experimental design, irrigation treatments were the main plots, replicated five times, and cultivars were split-plots within the main plots. The cultivars were 'Russet Burbank', 'Shepody', 'Frontier Russet', and 'Ranger Russet'. Irrigation treatments were arranged in randomized complete blocks and consisted of an adequately irrigated check and three deficit irrigation treatments (Table 1). The check treatment was irrigated when the soil water potential at 0.2-m depth reached –60 $J \cdot kg^{-1}$ (note that $J \cdot kg^{-1}$ = kPa) and had no more than the accumulated evapotranspiration (Et_c) since the last irrigation applied. The deficit irrigation treatments were irrigated when the SWP at 0.2-m depth reached –80 $J \cdot kg^{-1}$ and had a percentage of the accumulated Et_c applied at each irrigation: 1) 100%; 2) 70%; and 3) 50% until tuber set, then 70% for 6 weeks, and 50% thereafter. To reduce the risk of water movement below the top 0.3 m of soil, water applications at each irrigation were limited to avoid exceeding the water-holding capacity of the soil to a 0.3-m depth. For the check treatment, individual water applications did not exceed 30 mm. For the plots irrigated at –80 $J \cdot kg^{-1}$ with 100% Et_c replaced, individual water applications did not exceed 35 mm. The level of –80 $J \cdot kg^{-1}$ was chosen due to the SWP at which a single episode of water stress during tuber bulking could reduce 'Russet Burbank' tuber grade and quality at the experimental site (Eldredge et al., 1992, 1996).

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Table 1. Actual water applied plus precipitation, average soil water potential, and days with soil water potential drier than $-60\ J\cdot kg^{-1}$ in response to four irrigation treatments for potato. Crop evapotranspiration, Et_c, was estimated to be 666, 491, and 622 mm in 1992, 1993, and 1994, respectively.

Treatment		1992			1993			1994		
Irrigation criteria ($J\cdot kg^{-1}$)	Irrigation intensity (% of Et_c)	Total water applied (mm)	Avg soil water potential[z] ($J\cdot kg^{-1}$)	Time with soil water potential $<-60\ J\cdot kg^{-1}$ (days)	Total water applied (mm)	Avg soil water potential ($J\cdot kg^{-1}$)	Time with soil water potential $<-60\ J\cdot kg^{-1}$ (days)	Total water applied (mm)	Avg soil water potential ($J\cdot kg^{-1}$)	Time with soil water potential $<-60\ J\cdot kg^{-1}$ (days)
–60	100	589	–50	11	466	–30	3	544	–37	4
–80	100	566	–64	25	255	–41	12	380	–54	26
–80	70	411	–58	35	259	–51	21	356	–59	26
–80	50, 70, 50[y]	368	–72	44	64	–63	36	327	–60	31
$LSD_{0.05}$		46	22	18	39	14	12	70	17	14

[z] Average of daily, 8:00 AM measurements at 0.2-m depth from five plots, recorded a few days before tuber set through 7 Sept. each year.

[y] 50% of accumulated Et_c replaced until tuber set, then 70% of Et_c replaced for 6 weeks, then 50% of Et_c replaced until last irrigation.

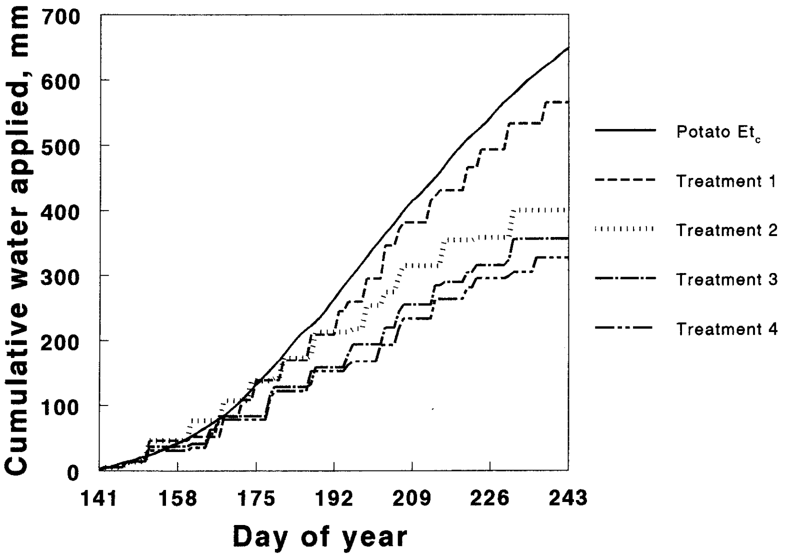

Fig. 1. Cumulative Et_c and water applied plus rainfall for potatoes submitted to four irrigation treatments in 1994. Treatment 1 was irrigated at $-60\ J\cdot kg^{-1}$ and had a target of 100% of Et_c applied. Treatments 2, 3, and 4 were irrigated at $-80\ J\cdot kg^{-1}$ and had targets of 100%, 70%, and < 70% of Et_c applied, respectively. Data for 1992 and 1993 were similar.

Plots were 13 rows wide (12 m) and 12 m long. Each plot was irrigated using sprinkler heads adjusted to cover a 90° angle at each corner of the plot. Water application rate was $10\ mm\cdot h^{-1}$ and the coefficient of uniformity for the sprinkler system, calculated according to Christiansen (1942) was 86%. All plots in a treatment were irrigated when the average SWP reached the treatment threshold value. Irrigations were initiated no sooner than one week before tuber set each year (Cappaert et al., 1994; Shock et al., 1992).

Soil water potential was measured in each plot by two granular matrix sensors (GMS; Watermark Soil Moisture Sensors model 200SS; Irrometer Co., Riverside, Calif.) centered at the 0.2-m depth and two GMS centered at the 0.5-m depth. The GMS were offset 0.15 m from the hill center (Stieber and Shock, 1995). Sensor readings were calibrated to SWP (Eldredge et al., 1993). The GMS were read at 8:00 AM daily starting a few days before tuber set each year. Crop Et_c was estimated using an AgriMet (U.S. Bureau of Reclamation, Boise, Idaho) weather station at the Malheur Experiment Station and a modified Penman equation (Wright, 1982). Crop Et_c was estimated and recorded from crop emergence until the final irrigation. Pan evaporation was measured in an adjacent standard evaporation pan.

The insecticide phorate {0,0-diethyl *S*-[(ethylthio) methyl] phosphorodithioate} at $3.4\ kg\cdot ha^{-1}$ was applied together with the preemergence urea in early May. The herbicides pendimethalin [*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] and metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methyl-ethyl) acetamide] were broadcast at $1.12\ kg\cdot ha^{-1}$ and $2.24\ kg\cdot ha^{-1}$, respectively, in mid-May, and incorporated immediately with a Lilliston cultivator.

Tubers were harvested from the middle 9 m of one 12-m-long row for each variety in each main plot in early October each year. Tubers were graded by market class (U.S. No. 1 and U.S. No. 2) and size (113 to 170 g, 170 to 283 g, and >283 g). Tubers were graded as U.S. No. 2 if any of the following conditions existed: growth cracks, bottleneck shape, abnormally curved shape, or two or more knobs.

A representative 20-tuber subsample from every cultivar in every main plot was put in controlled atmosphere storage (8 °C, 90% relative humidity) until early November, when tuber specific gravity and stem-end fry color were determined. Tuber fry color was determined according to the methodology described by Shock et al. (1994). Monetary values for the potatoes were calculated according to a 1996 potato growing and sales contract for processing potatoes (ORE-IDA Foods, Boise, Idaho). Potato production costs were calculated from data prepared by Malheur County Extension (Oregon State Univ., Ontario, Ore.) and were considered the same for all treatments except for harvest costs, which were calculated per unit of total yield. Irrigation costs were calculated from data prepared by Patterson et al. (1996) and were considered the same for all treatments except for the pump power costs, calculated per millimeter of water applied.

Data were analyzed by analysis of variance (ANOVA) as a split-plot design. Means separation was determined by the protected least significant difference test. Total yields and U.S. No. 1 yields and net profits averaged over varieties were regressed against applied water plus rainfall for the 3 years.

Results and Discussion

Water applications over time for all treatments were close to and less than the target Et_c values each year (Table 1; Fig. 1). The total amount of water applied during the season decreased in accordance with the experimental design. The accumulated growing degree days (10 to 30 °C) during the tuber bulking period were 931, 695, and 946 for 1992, 1993, and 1994, respectively. Precipitation during the tuber bulking period was 46, 57, and 7 mm for 1992, 1993, and 1994, respectively.

Tuber yields in the well irrigated treatments of this trial averaged $57\ Mg\cdot ha^{-1}$, while Malheur County, Ore., average yields in growers' fields were $46\ Mg\cdot ha^{-1}$ over the same years using the cultivars Shepody and Russet Burbank. In 1992, total and U.S. No. 1 yield, averaged across all four cultivars, were reduced by the most severe deficit irrigation treatment (Table 1). In 1993, U.S. No. 1 yield was reduced by irrigating at $-80\ J\cdot kg^{-1}$ with 70% or less of Et_c replacement (two most severe treatments). Total yield in 1993 was reduced by only the most severe treatment. In 1994, all deficit irrigation treatments reduced total and U.S. No. 1 yields. The lack of yield response to the two less severe deficit irrigation treatments in 1992 could be related to the smaller difference between the check treatment and the deficit irrigation treatments in water applied and days with SWP lower than

Table 2. Effect of deficit irrigation on potato tuber yield and grade (Mg·ha^{-1}) averaged over four cultivars for 3 years.

Irrigation threshold	Irrigation level	1992		1993		1994		Avg	
(J·kg^{-1})	(% of Et$_c$)	U.S. No. 1	Total	U.S. No. 1	Total	U.S. No. 1	Total	U.S. No. 1	Total
–60	100	44.6	63.6	35.1	49.7	40	57.9	39.9	57.1
–80	100	44.6	64	32.3	46.2	28.7	47.9	35.2	52.7
–80	70	40.8	59.2	30.8	45.4	29.9	48.9	33.8	51.2
–80	50, 70, 50^z	34.2	56.7	30.2	43	27.7	47.3	30.7	49
LSD$_{0.05}$		7.8	6.1	3.3	4.9	8.9	5.7	4.1	2.4

^{z}50% of accumulated Et$_c$ replaced until tuber set, then 70% of Et$_c$ replaced for 6 weeks, then 50% of Et$_c$ replaced until last irrigation.

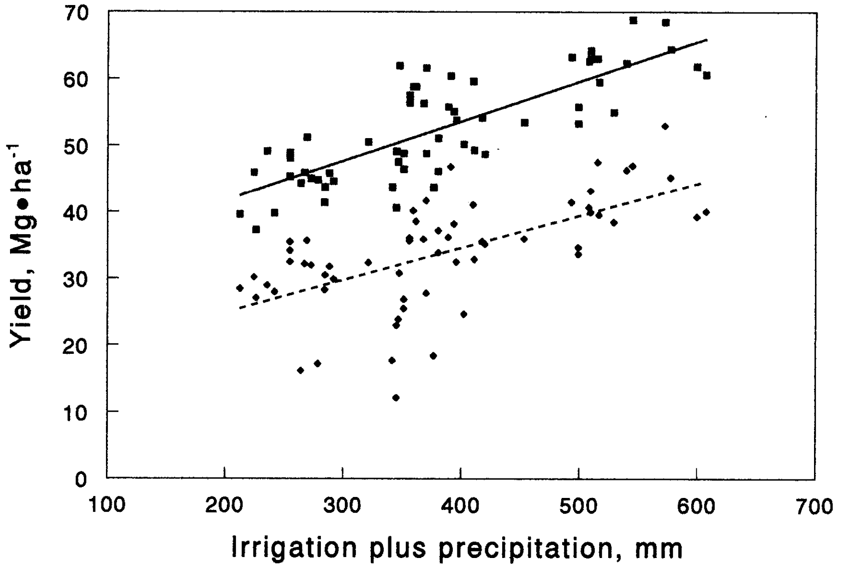

Fig. 2. Effect of irrigation plus precipitation amounts on potato tuber yield averaged over four varieties and 3 years. Regression equations are: Total yield (■): Y = 29.84 + 0.0595·X (R^2 = 0.63, P = 0.001), U.S. No. 1 yield (◆): Y = 15.28 + 0.0484·X (R^2 = 0.39, P = 0.001).

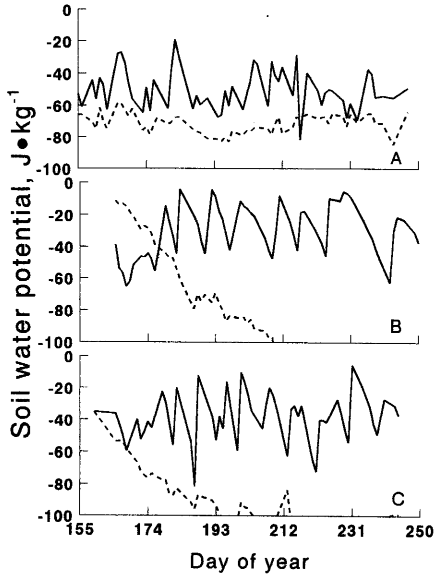

Fig. 3. Soil water potential over time for potatoes irrigated at –60 J·kg^{-1} replacing Et$_c$ in **A**) 1992, **B**) 1993, and **C**) 1994. Solid line: 0.2-m depth, dashed line: 0.5-m depth.

–60 J·kg^{-1} in 1992, than what occurred in 1993 or 1994 (Table 2). Yield reductions due to deficit irrigation were not as pronounced in 1993 as in 1992 or 1994. The weather in 1993 was cooler and wetter during the tuber bulking period (10 June to 24 Aug.) than in either 1992 or 1994. Both total yield and U.S. No. 1 yield increased with increases in water supply in each of the three years (Fig. 2).

Losses in potato yield and grade in response to deficit irrigation were in agreement with Caapaert et al. (1992), Eldredge et al. (1992), Hang and Miller (1986), Martin and Miller (1983), Miller and Martin (1983, 1987b), and Stark and McCann (1992).

In the present study, irrigation by cultivar interaction was significant only in 1992 for total and U.S. No. 2 yields. For 'Russet Burbank', U.S. No. 2 yield increased with deficit irrigation, whereas total yield was insensitive. In contrast, U.S. No. 2 yields for 'Frontier Russet', 'Ranger Russet', and 'Shepody' were insensitive to deficit irrigation whereas total yields were reduced. Other authors have found strong potato genotype by water stress interactions (Jefferies and MacKerron, 1993b; Martin and Miller, 1983; Miller and Martin, 1987b).

Deficit irrigation had an effect on tuber stem-end fry color in 1992 and 1993, but the differences were small. Deficit irrigation was only associated with reduced tuber specific gravity in 1994. Short-term deficit irrigation intensities (percent of Et$_c$ replaced) in this study were within the ranges that resulted in dark stem-end fry color and losses in tuber specific gravity in other studies. The lack of stem-end fry color response or consistent losses in tuber specific gravity to the season-long deficit irrigation in this study indicates that the potato plants could have become somewhat drought hardened in the manner hypothesized by van Loon (1981). Well watered potato plants subjected to irrigation deficits after tuber initiation during the middle of the growing season produce tubers with reduced specific gravity (Eldredge et al., 1996; Hang and Miller, 1986; Martin and Miller, 1983; Miller and Martin, 1987b; Stark and McCann, 1992). Miller and Martin (1987a) found that specific gravity of 'Russet Burbank' was reduced by deficit irrigation at 80% of Et$_c$ on a sandy soil. Stark and McCann (1992) reported that specific gravity was reduced and stem-end fry color was darker for 'Russet Burbank' subjected to deficit irrigation at 80% of Et$_c$ on a silt loam soil. In the study reported here, irrigations were managed to maintain root zone SWP higher than –80 J·kg^{-1}, thus attenuating the intensity of water stress resulting from the deficit irrigation treatments. The aforementioned studies, except Eldredge et al. (1996), despite using daily irrigations, did not use SWP feedback for irrigation scheduling.

The number of days with SWP at 0.2-m depth below –60 J·kg^{-1} increased with the change in the irrigation criterion from –60 to –80 J·kg^{-1} and with the decreases in applied water (Table 1). Water applications over time for all treatments were close to and less than the target Et$_c$ values each year (Table 1; Fig. 3).

In every year of the present study, SWP at 0.5-m depth remained lower than at 0.2-m depth for all treatments, and total water applied (irrigation plus precipitation) was less or slightly less than the estimated Et$_c$, suggesting that nitrate leaching potential was minimal (Fig. 3). Irrigation scheduling, using both target SWP and controlled water applications that did not exceed the water-holding capacity of the top 0.3 m of soil, resulted in total seasonal water applied being slightly less than estimated Et$_c$, even when the crop was irrigated at –60 J·kg^{-1}. The water deficit can be partly supplied from stored soil water at lower depths, as suggested by the increasing dryness of the soil at 0.5-m depth for the check treatment in 1993 and 1994 (Fig. 3). Alternatively, water savings can be accrued by initiating irrigations only after tuber set or, at the earliest, at full emergence (Shock et al., 1992).

Experimental results that are not entirely consistent with those in the present study were reported for 'Russet Burbank', 'Nooksack', and 'Lemhi' potatoes grown on loam and sandy soil and subjected to line source sprinkler irrigation treatments after early plant development and after early tuber bulking at Prosser and Patterson, Wash. (Martin and Miller, 1983; Miller and Martin, 1983). Starting with saturated soil, line source irrigation deficit treatments referenced to 100% Et$_c$ were based on 95% of pan evaporation for most of the remaining tuber bulking period. On the

Table 3. Effect of deficit irrigation on economic performance of sprinkler-irrigated potatoes, averaged across four cultivars for 3 years. All values are in U.S. $\$\cdot ha^{-1}$.

Irrigation threshold ($J\cdot kg^{-1}$)	Irrigation level (% of Et_c)	1992			1993			1994			Avg
		Production cost	Gross revenue	Profit	Production cost	Gross revenue	Profit	Production cost	Gross revenue	Profit	Profit
–60	100	5317	7550	2232	5084	6186	1103	5233	6830	1597	1629
–80	100	5322	7599	2276	5033	5749	716	5071	5425	353	1125
–80	70	5241	7071	1830	5022	5630	608	5080	5526	446	977
–80	50, 70, 50^z	5201	6666	1465	4997	5368	371	5058	4709	–289	720
$LSD_{0.05}$	Profit	95	821	726	87	620	538	91	868	779	360

^{z}50% of accumulated Et_c replaced until tuber set, the 70% of Et_c replaced for 6 weeks, then 50% of Et_c replaced until last irrigation.

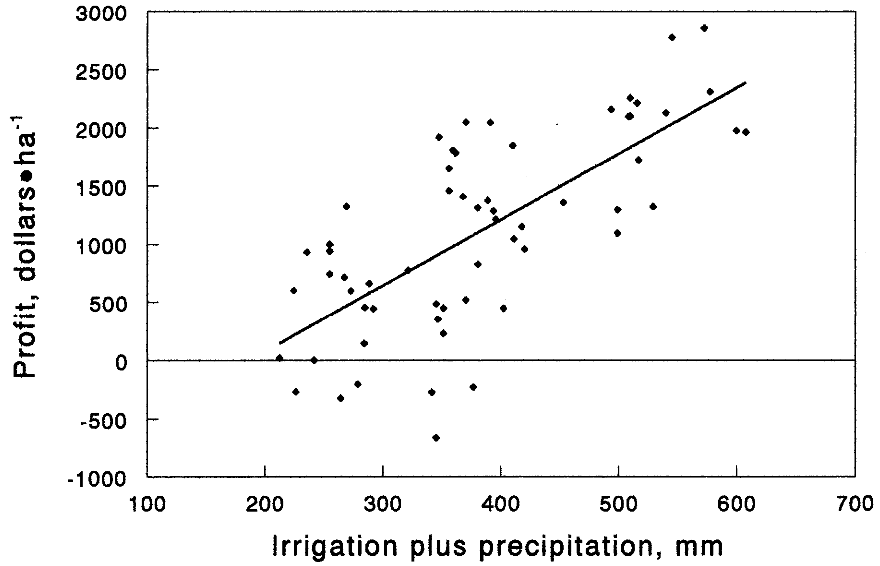

Fig. 4. Effect of irrigation plus precipitation amounts on profit of potatoes. Regression equation is: Y=–1058 + 5.68·X (R^2 = 0.51, P = 0.001).

loam, irrigation above 40% Et_c was harmful to tuber grade and tuber specific gravity, but total yield decreased with deficit irrigation. On the sandy soil, tuber yield and grade were reduced by deficit irrigation beyond 70% to 80% Et_c. Water application was measured using catch cans. On loam, the 100% Et_c treatment received 440 mm starting on 6 July 1979 and 490 mm starting on 12 July 1980. On sandy soil, the 100% Et_c treatment received 580 mm starting on 21 June 1979 and the 115% Et_c treatment received 650 mm starting on 1 July 1981. The amount of water applied and absence of soil water measurements may have resulted in excessive irrigation and leaching at these Et_c levels (Martin and Miller, 1983; Miller and Martin, 1983). In our trials, water applications at peak water crop use in July would have had to be increased by 21% to match 0.95 of the recorded pan evaporation, the 100% potato ET criterion used in several similar potato deficit irrigation studies (Hang and Miller, 1986; Martin and Miller, 1983; Miller and Martin, 1983, 1987a, 1987b).

Economic outcome. Deficit irrigation reduced gross revenues more than production costs (Table 3). Reductions in water applied resulted in small reductions in irrigation costs, because only electrical power for the pumping was reduced. Water costs independent of pumping did not decrease with decreased water application because water was charged by the irrigation district at a fixed fee per hectare.

In 1992 and 1993, only the driest treatment (irrigating at –80 $J\cdot kg^{-1}$ and replacing 50% of Et_c until tuber set, then 70% of Et_c for 6 weeks, then 50% of Et_c thereafter) resulted in a significant reduction in profits, over all cultivars. In 1994, all deficit irrigation treatments resulted in a reduction in profits. Over the 3 years, profits were increased with increases in applied water (Fig. 4). Stark and McCann (1992) measured yield, grade, specific gravity, and fry color for processing potatoes and these attributes declined with deficit irrigation.

The results of this study show that in two out of the three site years the mildest deficit irrigation of potatoes after tuber set did not result in statistically significant loss of yield or revenue using ANOVA. The deficit irrigation in this study was managed with a precision that might not be practical for growers. The environmental benefits of the check treatment were significant, with 10% less water applied than full estimated Et_c and with a low leaching potential. Since the reductions in production costs due to reduced water applications are small and since the check treatment resulted in significant environmental benefits, there would be no benefit from deficit irrigation drier than the check treatment. Deficit irrigation after tuber set, in the Treasure Valley of Oregon, could lead to greater risk to potato growers and could reduce the processing industry's competitiveness due to tuber yield and grade losses.

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